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GEOLOGICAL MAGAZINE

VOL. XCI. No. 3. MAY–JUNE, 1954

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The Petrography of Dickitic Sandstones in North Wales and Northern England

By FRANK SMITHSON

With an Appendix on the Differentiation of Dickite and Kaolinite by GEORGE BROWN

ABSTRACT

The clay mineral, dickite, is a common rock-forming mineral of many Carboniferous sandstones in North Wales and Northern England and of Middle Jurassic sandstones over much of North-East Yorkshire. It occurs as well-shaped authigenic crystals associated with highly altered mineral assemblages, including partly dissolved feldspar which is one of the probable sources of the alumina and silica.

I. INTRODUCTION

THE distribution of some of the rocks dealt with in the present paper has already been briefly described (Brown and Smithson, 1953). The subjects of the investigation were: (*a*) the distribution of sandstones containing well-crystallized clay minerals, and (*b*) the contribution made by such rocks to the clay mineral content of soils. Using microscopic methods for searching and X-ray methods (conducted by Mr. George Brown of Rothamsted Experimental Station) for precise identification, the first part has been carried far enough to indicate suitable sites for pedological work now in progress. Field and laboratory studies have, however, brought to light many facts which are chiefly of interest to the geologist and are therefore set out in the present paper.

Sandstones containing clay mineral crystals large enough to be seen under the microscope have long been known. Dick (1908) recorded kaolinite in Millstone Grit at Congleton, Cheshire, where " the mineral fills spaces between the grains of the grit and forms a loose aggregate of very small white scales some of which show perfect hexagonal outlines, whilst others are grouped in chlorite-like forms ". Greenly (1919) recording a similar occurrence in Millstone Grit in Anglesey, wrote that Dick had then reached the conclusions that " the importance of kaolinite as a rock-forming mineral was probably considerable ".

Similar material may also be associated with sedimentary rocks in nodules, veins, etc. (e.g. Tomkeieff, 1927; Hemingway and Brindley, 1948), but occurrences of this type are not dealt with here.

Dick recognized two varieties of kaolinite, but it was not until Ross and Kerr (1930, 1931) applied X-ray methods that the name *dickite* was given to Dick's " better crystallized type ". Much of the " kaolinite " recorded before 1930 may thus be dickite.

It is desirable at the outset to explain how certain terms are used in the present paper. The word *crystals* is applied only to particles recognizable as such under the microscope and to cleavage plates; it is not intended to imply that the other particles of clay material are non-crystalline. The term *clay mineral* might perhaps have been replaced in most places by the expression " dickite and/or kaolinite ", since these alone have been proved by the X-ray work. Although the well-shaped clay mineral crystals are probably all dickite, it will be preferable in places to refer to them non-committally as *clay mineral crystals*.

II. Detection and Separation of Dickite

Where such crystals occur in a sandstone they may be very quickly detected. For field observations the barrel of an old microscope was adapted as follows. A metal tube was made to screw on to the bottom of the barrel and within this tube there was fitted a second tube carrying a glass disc to act both as stage and object slip. Rough focusing was done by sliding this stage-tube, but the barrel possessed a fine adjustment adequate for the $\times$ 45 objective. The instrument being held like a telescope, the sky served as a light source.

The rock sample was scraped with a steel point so that particles fell on the glass stage (or slide, if using a normal microscope). If the material was very dry it was necessary to breathe on the glass before shaking off the coarse particles and examining those which adhered. Thus it was possible to test a large number of samples and decide which merited further study.

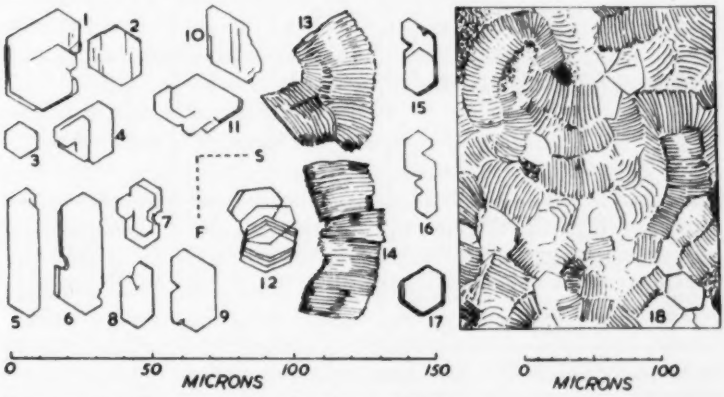
Selected sandstones were crushed with a pestle and mortar, trying to release the powdery constituents without breaking the sand grains. In some cases the material passing a 240 B.S. sieve was as much as 10 per cent of the rock, by weight, and consisted almost entirely of material which X-ray examination showed to be dickite. Nevertheless, as X-ray work proceeded it became evident that further purification was always desirable and the powders were therefore fractionated by repeatedly agitating with water and decanting after appropriate intervals decided by microscopic inspection of the suspension. In all cases the fastest settling fraction which contained quartz and feldspar was removed. Where dickite was suspected its identification by X-ray methods was usually facilitated if the very finest particles were

also removed and the final sample consisted largely of hexagonal plates, 5 to 20μ in diameter. In such cases the yield was improved if the original powder was gently rubbed with a rubber stopper to break up the rouleaux into plates.

III. Form and Mode of Occurrence of Dickite

Sandstones of various ages from many parts of England and Wales were examined by the rapid method described above, but positive results were obtained only for Carboniferous and Jurassic rocks in the districts enumerated in Section IV.

The dickite-bearing sandstones are yellow, buff, near-white, grey, or pink, often with white specks visible to the naked eye and occasionally brown specks of limonitic matter. The extracted powders are somewhat paler or whiter than the rocks.



Text-fig 1.—Camera lucida drawings of dickite.
Millstone Grit, Anglesey: 1–11 Cleavage plates. 12 Crystal breaking up into plates. 13–14 Prisms or rouleaux. 18 Thin section.
Middle Jurassic, Yorkshire: 15–17 Cleavage plates.
Broken lines (F, S) indicate fast and slow vibration directions for 1–11, 15–17 and, approximately, for 14.

The appearance of the mineral under the microscope is shown in Text-fig. 1. Thin sections prepared from dickite-rich sandstones after hardening with bakelite show much of the mineral occupying spaces between closely packed sand grains, though some larger dickite areas occur. With high magnification thin sections show closely packed rouleaux, only a few presenting hexagonal sections to the observer. The powders contain both rouleaux and plates, the latter being hexagons, some almost regular, others elongated in one direction or another. Most of the plates are 5 to 20μ across, but in the Millstone Grit of Anglesey some measure 50μ.

The mean refractive index of Yorkshire and Anglesey dickite is about 1·565 for sodium light and the birefringence about 0·005. The rouleaux are readily stained by malachite green and become pleochroic (Fast: colourless to lilac. Slow: blue green), but with thin plates the staining appears feeble. Ross and Kerr (1930, p. 168) found dickite " not strongly stained by dyes, not pleochroic ", probably because the material tested was " clear, transparent thin crystal plates ".

TABLE I.—FREQUENCY OF DICKITE, KAOLINITE, AND ASSOCIATED HEAVY MINERALS IN SOME BRITISH SANDSTONES

		Clay mineral crystals	Results and numbers of X-ray tests	Garnet	Authigenic anatase	Authigenic brookite	Outgrowths on tourmaline	Outgrowths on zircon	Pyrite	Ankerite
MIDDLE JURASSIC	YORKSHIRE N.E. Moorlands	C	D 7 D′ 3 Dk 1	VS	C	C	—	C	VS	—
	YORKSHIRE Howard Hills and Scarborough district.	S	K 2 K′ 3	F–C	F	F	—	S	VS	—
		A	K 3 K′ 1							
" MILLSTONE GRIT "	NORTHUMBERLAND Slaley . .	C	D 1	—	—	F	—	C	—	—
	YORKSHIRE Ellingstring .	C	D 2	F	S	C	—	C	—	—
	ANGLESEY Bodorgan	C	D 1	F	S	—	—	—	S	C
	DENBIGHSHIRE Garth . .	C	Dk 1	S	—	C	—	—	—	—
LR. CARBONIFEROUS	ANGLESEY AND CAERNARVONSHIRE . .	F	D 1	—	S	—	C	—	C	—

A or—Absent
VS Very scarce
S Scarce
F Fairly common
C Common
D Dickite
K Kaolinite
k Kaolinite, small amount
The significance of the dash (') is explained in the Appendix.

The fact that a mineral so soft and cleavable, occurs in the form and manner described shows that it is authigenic. Since many of the heavy minerals with which it is associated are also authigenic or exhibit authigenic outgrowths the distribution of dickite and that of the heavy minerals are discussed together in the next section.

IV. DICKITE AND THE ASSOCIATED HEAVY MINERALS

Most of the minerals in these rocks are the stable species common in British sediments, yet nearly all the groups of rocks described present some unusual features (Table I).

Lower Carboniferous.—In the Lower Carboniferous sandstones of Anglesey and Caernarvonshire some of the tourmaline grains are corroded at one end and have outgrowths [1] at the other (Smithson, 1953, pl. iii). Out of eleven sandstones examined, six were dickite-bearing and all six contained this peculiar tourmaline, as did two samples which yielded no dickite. Garnet was not seen, but may have been present originally, since corroded garnet appears in the associated calcareous beds which would tend to protect this mineral.

" *Millstone Grit.*"—Although many samples of this rock from the north of England were examined, in only two localities (Slaley, near Hexham; Ellingstring, near Masham) did the microscopical examination reveal many clay mineral crystals. In both cases the mineral was dickite, which was associated with a heavy assemblage showing few species, but contained numerous grains of zircon with outgrowths, a phenomenon first observed in the Millstone Grit by Butterfield (1936).[2]

In Anglesey the dickite-bearing grit contains corroded garnet, but in some ankeritic portions of the rock this mineral appears to have been protected as described in Section V.

Between Mount Pleasant and Garth in Denbighshire, the " Aqueduct Grit " of the Cefn-y-fedw Sandstone Series is described in the Survey Memoir (Wedd *et al.*, 1927) as a rather coarse grit with interstitial kaolin. X-ray examination now suggests that the dominant clay mineral is dickite with some kaolinite which is mostly in the finer fractions. Here, too, garnet has suffered corrosion.

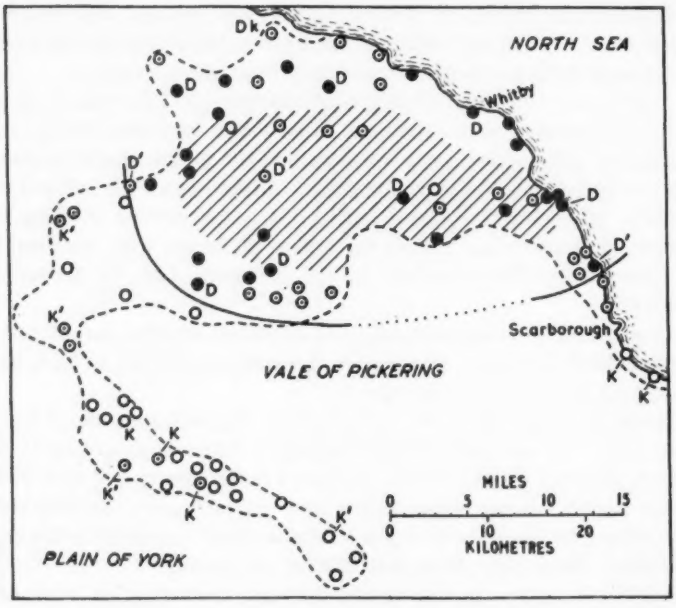
Middle Jurassic.—In the Middle Jurassic sandstones of Yorkshire the relationships between the clay minerals and the associated mineral assemblages have been examined more thoroughly to find what differences occur on passing from a region where dickite is common to one where it cannot be detected (Text-fig. 2). Mineral distribution maps made earlier had shown an oval area where the rocks contain very few detrital species and where certain authigenic minerals are abnormally abundant.[3] Garnet, for example, is almost completely absent from the shaded area in Text-fig. 2, but becomes common within about 15 miles, whilst the distribution of zircon with outgrowths is roughly the reverse. Where garnet is scarce it shows clear evidence of corrosion, and where it is absent it has probably been removed by solution.

[1] Tourmaline grains with outgrowths at one end are known in sedimentary rocks in U.S.A. (Alty, 1933).

[2] There appear to be only two other records of such grains in sedimentary rocks (Smithson, 1937; Bond, 1948).

[3] Many hundred samples were used for this work (Smithson, 1939, 1941, 1942), but because of war damage only a part of the collection remained for the present clay mineral studies.

Before the X-ray work was done, the distribution of clay mineral crystals was studied microscopically by the rapid method described in Section II, so as to demarcate an area where most of the rock samples (129 out of 160) contained this material (Text-fig. 2): eleven of the



TEXT-FIG. 2.—Distribution of dickite in the Middle Jurassic sandstones of Yorkshire (79 localities with 1 to 14 samples from each; 252 samples).

Broken line: Limit of M. Jurassic outcrops, generalized and ignoring Liassic inliers. *Bold line*: Limit of localities with visible clay mineral crystals common or persistent. *Shading*: Garnet very scarce.

Frequency of visible clay mineral crystals in richest sample at each locality:—

Black circle: Common or abundant. *Plain circle*: Absent. *Dot in circle*: Scarce to fairly common.

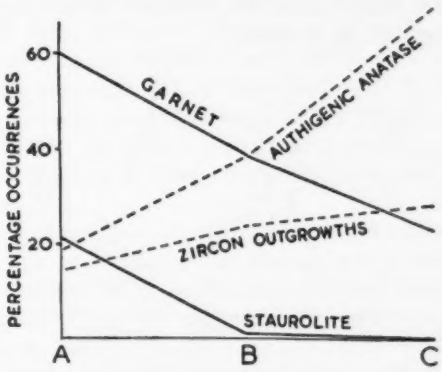
X-ray identifications (one sample from each locality indicated):—

D—dickite. K—kaolinite. k—kaolinite, a small amount. The significance of the dash (') is explained in the Appendix.

richest were chosen for X-ray tests, all of which showed dickite to be the dominant clay mineral. Beyond the limits of this area only fifteen out of ninety-two samples yielded any of the crystals and in none did they form more than a small proportion of the clay mineral content. Five of this type were chosen, together with four in which no crystals were seen in the clay material, and on subjecting these to X-ray examina-

tion all nine were found to have kaolinite as the dominant clay mineral.[1] More detailed results are given in Table I and in Text-fig. 2. Both show that where the crystals are abundant they consist of dickite, and the map shows that dickite is common in or near the area where mineralogical change, typified by the destruction of garnet, reached its maximum.

The relationship between the clay minerals and the heavy minerals can also be shown graphically. In 223 cases both a heavy mineral slide and a rapid clay mineral separation were available, and these were classified into three groups according to the appearance of the clay



TEXT-FIG. 3.—Relation of heavy mineral to visible clay mineral crystals in the Middle Jurassic sandstone of Yorkshire.

Plotted horizontally are three groups of samples in which visible clay mineral crystals are—A, absent; B, scarce to fairly common; or C, common.

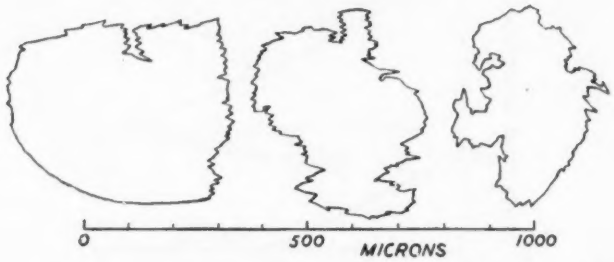
mineral: (A) ninety-five samples with no visible crystals, (B) eighty-eight crystals rather scarce, and (C) forty with crystals common. Text-fig. 3 shows "percentage occurrences" of some of the heavy minerals for the three groups, e.g. in A, garnet was found in fifty-seven of the ninety-five samples, i.e. in 60 per cent of them. Values for garnet and staurolite, both detrital, diminish from A to C, but for anatase and outgrowth on zircon, both of which are authigenic, values increase from A to C, i.e. as the crystals which are to be regarded as dickite become more common.

Thus both mapping and graphical work suggest that the formation of dickite and the alteration of the heavy minerals tend to occur together and may be due to the same underlying causes.

[1] Nevertheless the visible crystals may be dickite since they probably form too small a proportion of the powder to affect the X-ray diffraction photograph.

V. The Light Minerals

The light minerals have been studied after separating (1) the fraction which floats on bromoform and consists chiefly of quartz with white mica and feldspars, and (2) the small fraction which floats on a liquid slightly lighter than quartz and which usually contains a large proportion of potash feldspar and sometimes a little albite. This work has not covered all the samples studied for clay minerals, but enough has been done to show that, in these rocks, quartz grains enlarged by authigenic quartz and feldspar grains made ragged by corrosion are regularly associated with dickite. Thus in the Middle Jurassic these phenomena are conspicuous in the dickite-rich sediments but absent where kaolinite is the characteristic clay mineral.



Text-fig. 4.—Outlines of microcline grains from an ankeritic portion of the Millstone Grit, Bodorgan, Anglesey.

The most instructive examples of feldspar corrosion were found in a specimen from the Millstone Grit, Bodorgan, Anglesey, where in general the rock contains little feldspar. The specimen was ankeritic and was treated with dilute hydrochloric acid to obtain a sand for heavy liquid separation. The fraction lighter than quartz consisted chiefly of rouleaux of dickite and grains of microcline. Some of the latter were rounded, most were extremely ragged from corrosion and a few had part of their outline rounded and part ragged (Text-fig. 4). The raggedness is so delicate that it must be due, not to fracture, but to solvent action against which some of the grains were partly or wholly protected by the cementing material. Garnet in the heavy residue shows a similar phenomenon, some of the grains being well rounded, some etched over part of their surface in a rhombic dodecahedral pattern, and some so much eaten into that none of the original surface remains. Garnet, like microcline, is commonest in the ankeritic parts of the rock. The microcline grains which have suffered partial solution are otherwise unaltered, retaining their optical properties and showing their characteristic twinning with great clearness.

VI. Conclusion

It appears to be agreed (Taylor, 1952; Grim, 1953) that more must be known about the distribution of clay minerals in recent and ancient sediments before the origin of the various species can be fully understood. It will be more useful, therefore, to summarize pertinent facts which may ultimately help to explain the occurrences of dickite and kaolinite described above, than to discuss their origin at length.

Source of Al_2O_3 and SiO_2.—Authigenic clay minerals are often supposed to be derived from allothigenic clay minerals. Greenly (1919), seeing no feldspar in the Millstone Grit of Anglesey except a little unaltered albite, concluded that the mineral now known as dickite resulted from the recrystallization of a matrix of aluminous mud. The finding of microcline in parts of this rock under circumstances which suggest that it may have been more widespread, now points to microcline as one likely source of the dickite and the authigenic quartz. Since microcline appears to have gone into solution, the dickite and quartz may have crystallized some distance from the parent feldspar grain.

Conditions of Deposition.—Several authors have related the type of clay mineral to the conditions of deposition of the containing sediment. For example, Millot (1952) finds kaolinite particularly characteristic of certain types of freshwater deposits. The Millstone Grit and the Yorkshire Middle Jurassic, though the latter has long been termed the Estuarine Series, are chiefly deltaic (Gilligan, 1919, Hemingway, 1949) and are characterized by dickite or kaolinite. Arenaceous marine beds in the Yorkshire Middle Jurassic appear to contain some dickite,[1] but the mineral is much less common than in the Deltaic beds. The Lower Carboniferous sandstones considered here contain no marine fossils but plant remains are frequent.

Post-depositional Changes.—In the Middle Jurassic dickite is associated with other authigenic minerals and with impoverished and corroded detrital assemblages. All these phenomena reach their maxima in a roughly oval area lying on the main tectonic axis of the region, and are unrelated to the palaeogeography of the period as deduced from grain-sizes of zircon. They are evidently due to changes which took place after deposition and appear to be dependent upon depth of burial (Smithson, 1941, p. 111). This is not to say that conditions of deposition are unimportant, for it is possible that certain depositional and post-depositional conditions are equally essential before certain post-depositional changes can take place.

[1] Hemingway and Brindley (1949) found dickite in this region " in cracks and septaria in rocks of marine and deltaic origin and replacing the shell-substance in fossiliferous marine ironstone " which " indicates migration through the rock after diagenesis, probably in solution and not as particles ".

Appendix

The specimens of kaolin-bearing sandstone with which this work is concerned were not chosen for their suitability for clay mineral identification but for the light they might shed on the problem of clay mineral distribution. The difficulties encountered in the X-ray examination vary from specimen to specimen and are due to the contamination of the kaolin [1] with other minerals. For the Millstone Grit from Bodorgan, Anglesey, that part of the crumbled rock which had passed a fine sieve was readily shown to be dickite contaminated with quartz; but material obtained in a similar way from Middle Jurassic sandstone in Yorkshire contained so much quartz and feldspar that further separation and X-ray examination were necessary before the clay mineral could be identified and the method of separation (described in Section II) approved as a routine technique.

The material used for X-ray examination was not a clay-fraction in the sense of consisting of particles of clay size, i.e. equivalent spherical diameter $< 2\mu$. The separation was designed to concentrate the relatively large clay mineral crystals whenever these were present and to remove the small amount of clay-size material.

The only clay materials which have been identified are dickite and kaolinite. X-ray diffraction patterns of the two minerals, though similar, afford a ready method for differentiation and if the sample is a mixture of these two alone, a rough quantitative estimation can be made. As the amount of material other than kaolin increases, quantitative estimation becomes more difficult and if kaolin is a minor constituent even specific identification may be impossible. If refined techniques are used it becomes easier to identify the minerals but with complex mixtures these, too, may fail. Special techniques have not been used in this project and the identifications have been grouped into classes according to the degree of success in identifying the two minerals.

Class 1.—In Table I and Text-fig. 2 these are denoted D for dickite and K for kaolinite. Each separation consists chiefly of *one* of these minerals with a small amount of non-clay minerals; if a second kaolin mineral is present it is not likely to exceed 15 per cent.

Class 2.—These are denoted D′ and K′. Here again, only one of the kaolin minerals has been identified in each separation but because of larger amounts of non-clay minerals than in class 1, it would be possible for appreciable amounts (up to 25 per cent) of a second kaolin mineral to remain undetected.

Class 3.—In three separations there is positive evidence that dickite is accompanied by kaolinite. These are:—

[1] Kaolin in this note means a member of the kaolin group of minerals (see Brindley, 1951).

Two separations from the Aqueduct Grit ("Millstone Grit") between Mount Pleasant and Garth, Denbighshire.

(*a*) Material of observed particle diameter 5–30μ; mainly dickite with a little kaolinite (10–25 per cent).

(*b*) Material of observed particle diameter 2–10μ; dickite and kaolinite in about equal amounts.

As the amount of fraction (*b*) is small in proportion to (*a*), the kaolin of this rock is recorded in Table I as Dk, i.e. mainly dickite with a little kaolinite.

One separation from Middle Jurassic sandstone, near the Ellerbeck Bed, Brotton, Yorkshire. The kaolin is mainly dickite with a little kaolinite (10–25 per cent). This is recorded as Dk in Table I and also in Text-fig. 2 for the most northerly locality on the map.

Class 4.—This class, where the amount of impurity is so large that the kaolin cannot be differentiated, must be mentioned, for although it was possible to overcome this difficulty by adequate separation when dealing with material from kaolin-bearing sandstones, it still remains a serious obstacle with materials from derived soils. Dr. Smithson finds that the soils contain hexagonal plates similar to the dickite of the parent rock, but the best separations so far give X-ray diffraction patterns which indicate nothing more definite than a kaolin.

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Lamellibranchia and Plants from the Lower Karroo Beds of Northern Rhodesia

By GEOFFREY BOND

(PLATE IV)

ABSTRACT

A small collection of non-marine lamellibranchs and plants from the Madumabisa Shales of the Gwembi district of Northern Rhodesia is described. It includes a new species of the genus *Kidodia*, *Palaeomutela rhomboidalis*, and *P. neglecta*, associated with *Glossopteris indica*. The Madumabisa Shales may be correlated with similar beds in Southern Rhodesia assigned to the *Tapinocephalus* zone of the South African Lower Beaufort Series, and are of Upper Permian age.

A SMALL collection of lamellibranchs and plants found by Mr. H. S. Gair, of the Northern Rhodesian Geological Survey, was sent to the writer for examination. They were found in the Siambabala Valley in the Gwembi district, which lies between the Zambezi River and the escarpment bounding the plateau of Northern Rhodesia. The matrix is impure limestone and the lamellibranchs consist almost exclusively of well-preserved internal casts. Although solution has in most cases destroyed the shell and external features, it has fortunately exposed details of hinge structure and muscle scars on which classification so largely depends in this group. The plants are preserved as impressions in shaly mudstone.

MOLLUSCA—LAMELLIBRANCHIA

Fam.: ANTHRACOSIIDAE Amalitsky, 1892

Kidodia coxi sp. nov. Pl. IV, figs. 1 *b*, 1 *c*, 2, ?3

Diagnosis.—The shell is equivalve and inequilateral. Umbones are obtuse, level with the postero-dorsal margin and placed one-quarter of the length of the shell from the anterior margin. The postero-dorsal margin is only slightly convex. The anterior margin slopes steeply, making an angle of a little less than 100° with the posterior part of the hinge. The anterior end is rounded, the posterior curve of the shell smoothly rounded and passing into the ventral border, which is slightly curved; the general outline of the shell is somewhat triangular.

Among the specimens available are two shells of similar shape with the external features preserved. The ornament consists of 10–12 regular concentric rugae. As the internal features of these particular specimens are not known it cannot be stated with certainty that this ornament belongs to the species under description.

The internal features are as follows. In the right valve there is a strong anterior lateral tooth, which is practically straight, and there is a slight, elongated depression near the hinge margin. In the left valve there is a long, well defined posterior lateral tooth, separated from the hinge margin by a long depression. There are no cardinal teeth. The anterior adductor scar is pronounced, pear-shaped, and pointed dorsally. The posterior adductor impression is so faint that it can hardly be made out. The pallial line is entire and faintly impressed.

Holotype.—Left valve in Geological Department of National Museum of Southern Rhodesia. Reg. No. 7557. The same hand specimen also includes a right valve of a larger individual.

Paratype.—Right valve in Geological Department of National Museum of Southern Rhodesia. Reg. No. 7558. The same hand specimen includes several other valves.

Remarks.—The genus *Kidodia* was erected by Cox (1936) to include the single species *K. stockleyi* from the Lower Beaufort Beds of Tanganyika Territory. It remained monotypic until Frenguelli (1945) described a second species *K. picardi* from Triassic rocks in Argentina. The hinge characters of the Northern Rhodesian specimens leave no doubt that they should be referred to *Kidodia*, and they differ sufficiently from the two known forms to warrant description as a new species. The differences are mainly in the angle made by the two parts of the hinge. In *K. stockleyi* it is about 145° and in *K. picardi* it is about 120°, whereas in the new species it is about 100°, and these different angles give a distinctive shape to each species. It is proposed to name the new species *Kidodia coxi* in honour of Dr. L. R. Cox, F.R.S., who erected the genus to which it is referred and who has given considerable help to the writer in connection with Karroo palaeontology.

Palaeomutela rhomboidalis (Sharpe), Pl. IV, fig. 1 *a*

A few shells show the hinge characters of the genus *Palaeomutela* as they have pseudo-taxodont teeth in part of the hinge. It is difficult to be sure of specific reference in shells of this type, but the general shape is similar to that of the forms referred to *P. rhomboidalis* by Cox, whose interpretation of the group is followed here.

Material.—Specimens in the Geological Collection of the National Museum of Southern Rhodesia. Reg. No. 7557, on the same hand specimen as *Kidodia coxi*. Locality and horizon as for that specimen.

Palaeomutela neglecta (Jones)

A few of the specimens with pseudo-taxodont hinges differ in shape from *P. rhomboidalis* and more closely resemble *P. neglecta* (Jones), to which species they are referred.

Material.—Geological Collection of the National Museum of Southern Rhodesia. Reg. No. 7557. Locality and Horizon as for *Kidodia coxi.*

Palaeonodonta sp.

Among the internal casts there are shells which appear to have completely edentate hinges. This type of hinge is characteristic of the genus *Palaeonodonta*, but the shells cannot be referred to it with certainty, since the casts are friable, and it is possible that fragile teeth may have been lost. Better material is needed before it can be stated with confidence that the genus is represented.

Material.—Geological Department, National Museum of Southern Rhodesia. Reg. No. 7557.

Plantae

Fragmentary plants are closely associated with the non-marine lamellibranchs. All the specimens so far examined can be included in two forms. *Glossopteris indica* Schimper can be named with some assurance and some longitudinally ribbed stems are of the type usually called *Phyllotheca* sp.

Discussion

The list of forms so far found is therefore:—

Kidodia coxi sp. nov.
Palaeomutela rhomboidalis (Sharpe)
Palaeomutela neglecta (Jones)
Palaeonodonta sp.
Glossopteris indica Schimper
Phyllotheca sp.

Kidodia coxi has not yet been found in Southern Rhodesia, but *Palaeomutela rhomboidalis* and *P. neglecta* occur, with other species of *Palaeomutela*, *Palaeonodonta*, gastropods, ostracods, phyllopods, and an impoverished *Glossopteris* flora, including *G. indica* and *Phyllotheca* sp., in the middle division of the Madumabisa Shales. As this association has been found at a number of localities, all of which seem to lie on about the same horizon, it has been suggested by the writer (Bond, 1946, 1952) that it is characteristic of this part of the succession. The composition of the Northern Rhodesian assemblage, meagre though it is, suggests correlation with the Middle Madumabisa Shales of Southern Rhodesia, and the position of the fossiliferous beds in the Northern Rhodesian sequence supports this conclusion. They lie above the coal-bearing shales and are succeeded by about 1,000 feet of massive blue calcareous mudstones with layers of calcareous

concretions. The base of the Escarpment Grit, the lowest member of the Upper Karroo, lies above these mudstones. The succession is very like that found in parts of Southern Rhodesia on the other side of the Zambezi River. The invertebrate assemblage from the Middle Madumabisa Shales in Southern Rhodesia has been correlated with the Lower Beaufort of the Union of South Africa, and Boonstra (1946) has placed it in the *Tapinocephalus* (lowest) zone of the Lower Beaufort reptile succession as developed in South Africa.

It is concluded, therefore, that the fossil-bearing horizons at which *Kidodia coxi* was found also belong to the *Tapinocephalus* zone of the Lower Beaufort. In terms of the European time scale their age is Upper Permian.

Very little has been published previously on fossils from the Karroo rocks of this part of Northern Rhodesia, and the records that existed did not lead to very close correlation.

The writer expresses his thanks to Mr. H. S. Gair for sending this material for examination; to Mr. W. C. Schollum, A.R.P.S., of Bulawayo, for taking the photographs which illustrate the paper, and to Mr. W. H. Reeve, Director of the Geological Survey of Northern Rhodesia, for permission to publish these results.

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EXPLANATION OF PLATE IV

Fig. 1.—*a Palaeomutela rhomboidalis* (Sharpe). Internal cast. × 2.
b Kidodia coxi sp. nov. Left valve of holotype. Internal cast. × 2.
c Kidodia coxi sp. nov. Right valve. × 2.

Fig. 2.—*Kidodia coxi* sp. nov. Cast made to reproduce in positive the internal characters of the left valve shown in Fig. 1 *b*. × 2.

Fig. 3.—Two shells showing ornament, which may be exteriors of *Kidodia coxi*.

FIG. 1.

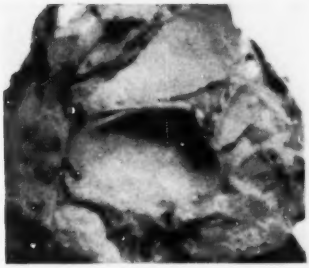


FIG. 2.

FIG. 3.

LAMELLIBRANCHIA FROM N. RHODESIA.

Thrusting and other movements in the Durham Permian

By C. T. Trechmann

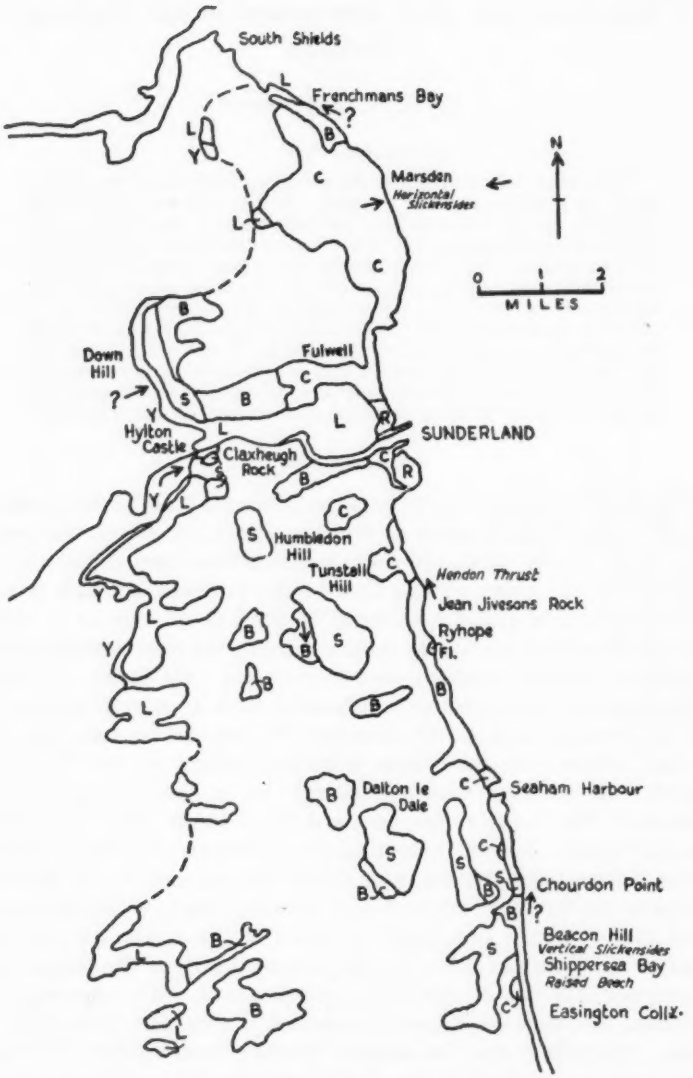
Abstract

The Permian in Durham is the most internally disturbed of the newer or covering beds of England. In deep borings it is a dark dolomitic rock full of sulphates and chlorides; at the surface it has quite a different appearance. The Permian and overlying Secondary beds seem to have been lowered by downwarping. During the subsequent differential uplift and denudation the area remained a land surface and the sulphates were removed by penetrating water, not by subaerial weathering. Horizontal and low angle thrusts occur in the Sunderland area above about the middle of the underlying Coal Measure basin. The movements may have been induced by diminution in rock volume following solution and segregation accompanied by attraction or packing together of the mass of the formation.

Introduction

DISLOCATIONS having the nature of thrusts occur in the northern area of the Permian in Durham. They are seen on the coast for about 6 miles north and south of Sunderland, and inland on the escarpment at Claxheugh and Down Hill. Disturbances such as the Marsden breccia gashes were noted by Prof. G. A. Lebour in 1886. Dr. D. Woolacott studied the thrusts in detail, but he conceived rather grandiose notions regarding their importance. He wrote : "This thrusting was most probably connected with a general movement of the North of England strata against the horst of the Lake District massif, which may have been subsidiary effects of the Miocene uplift, that produced such marked changes in the physiography of Britain." He says there has been a decrease in the lateral extension of the Permian. In 1913 I recorded the occurrence of a mass of anhydrite 260 feet thick, that underlies the ground occupied by the Warren Cement Works at Hartlepool and probably part of the harbour, and showed by the occurrence of fossils of the middle part of the reef in the cores just below it, that it formed part of the Magnesian Limestone and not of the higher salt measures. It is apparently a remnant of a once much greater extension of sulphates in the formation. I suggested that the collapse resulting from solution of these may have caused much of the sliding and thrusting; but why there should have been horizontal movements and not merely collapse and becciation is not so clear.

The displacements, though limited in extent, have the appearance of tectonic thrusts and in at least two cases older beds have been thrust up and over newer ones. At Claxheugh the lower limestone divides and part is thrust over middle reef; at Hendon on the coast, middle is



TEXT-FIG. 1.—A sketch map of the area of the Durham Permian where the thrusting has occurred. Arrows indicate the thrusts and the direction in which they may have gone. R, Hartlepool and Roker dolomite. C, Concretionary limestone with *Filograna* bed at the top. Fl, Flexible limestone. S, Shell limestone reef, including zones A, B, C, and D in ascending order. B, Brecciated rock on east and west flanks of the reef. L, Lower Magnesian Limestone with Marl Slate at the base. Y, Yellow Sands.

thrust over concretionary upper beds. Where a reef knoll is firmly established, as at Humbledon Hill, with complete faunal sequence, one does not see thrusts. In Durham as in the Alps, thrusting seems to be connected with rock facies differences, as well as with metamorphism. The area of thrusting in Durham lies about the middle of the Coal Measure basin, but no connection is known with any disturbances in the Carboniferous below. As the Coal Measure basin became accentuated by the rise of its rim, there may have been a tendency to contract, which possibly affected the overlying Permian. The other

TEXT-FIG. 2.—Section of the cliff-face at Claxheugh Rock, 4 miles west of Sunderland, showing the upper and main thrusts.
UCM, Upper Coal Measures faulted against Yellow Sands. YS, Yellow Sands with current bedding. MS, Marl Slate. L, Lower Magnesian Limestone with a few *Spirorbis* and *Martinia clannyana*. SL, Shell Limestone reef rock, massive but bedded in places with an impoverished fauna. T,T, Higher thrust carrying Lower limestone up and over part of the reef. TT, Main thrust, the under surface of the reef rock has broad grooves and traces of gypsum. In the depression the reef material has been reassorted and contains grains from the Yellow Sand and separated brachiopod valves, and is partly overthrust by Lower limestone. East of this the Lower limestone and Marl Slate are thrust out and the reef rests on Yellow Sands.

instances of disturbance in the newer rocks of England are the contortions of a vertical band in the Chalk at Flamborough, and the upturning of Secondary and Tertiary strata along the South Coast.

The Double Thrust at Claxheugh, 2½ miles West of Sunderland.

Claxheugh Rock about 120 feet high, on the south bank of the Wear, offers the most important display of thrusting in the Permian. There are two thrusts, a lower and an upper one. The lower one thrusts the middle massive reef over the lower beds. Broad rounded grooves are seen on the overhanging under surface of the reef rock. They are aligned S.W.–N.E. at the west end, W.S.W.–E.N.E. near the middle, and nearly E.–W. at the east end. Some of the curving grooves and ridges

are 2 inches wide, some are more prominent than the rest. Although the thrust has been powerful enough to cut out part and then all of the very hard lower limestone, one does not see smoothening or striation as on an ordinary faulted surface. Followed from west to east the thrust cuts up and then down across the bedded lower limestone, then comes a depression, and east of this the reef cuts the limestone out altogether and rests on the yellow sands. In the depression the lower and middle beds are confused and the lower is partly thrust over reef rock. Pieces of the reef here contain grains and streaks of dull sand grains derived from the Yellow Sands. These are not seen in the reef where it still rests on lower limestone. The shell limestone here contains broken Polyzoa and separated valves of *Spiriferina* and *Camarophoria*. This is curious because elsewhere in the Permian the brachiopod valves are still fixed together. Some pieces of the lower limestone also are incorporated in the reef rock and seem to merge into it. This suggests that some sort of disintegration and redeposition was going on while the thrusting was in action, and caused the brachiopod valves to become torn apart. Between the thrust surfaces is a thin argillaceous and dolomitic layer, a sort of mylonite. The surface is coated with radiating gypsum crystals, which also penetrate the joints for about an inch. The gypsum seems to be original and may have acted as a lubricant and have been preserved in the layer of clay. It suggests that the thrusting occurred before the complete removal of sulphates from the formation.

The Shell Limestone at Claxheugh Rock is not its lowest part ; the fossils include *Strophalosia*, *Liebea hausmanni*, *Byssoarca*, *Bakevellia*, etc., but the horizon is well above that of *Productus horridus* and *Spirifer alata*, or Reef A. The missing 100 feet or so, may never have been deposited, may have been represented by anhydrite, or may have been thrust out of position.

At the east end of the section the overthrust surface of the Yellow Sand slopes southwards at 45 degrees towards the railway cutting and the Ford Lime quarry.

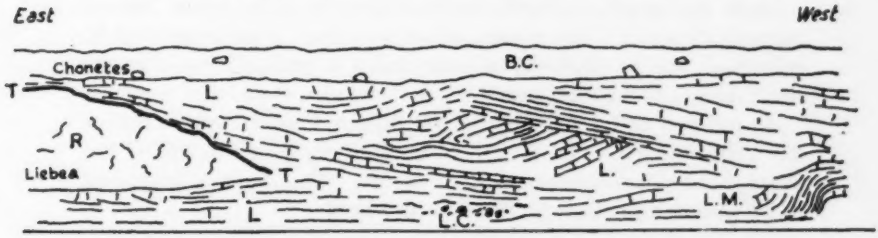
The higher thrust is seen at the north-west corner of the rock section, and in the railway cutting south of and parallel to the rock face. Here it was observed by Dr. Woolacott, but it is now much better exposed in the Ford quarry which has been deepened and widened since his time. It is well seen on both the north and south facing sections of the quarry and the disturbances showed variation as quarrying continued during the last twenty years.

In the quarry it is evident that the lower limestone has divided along the bedding, part remaining below and part has gone up at an angle of about 35 degrees over the west edge of the reef.

The relation of the upper thrust to the main thrust in the rock face is not clear, nor whether they both moved together or at different

times. The upthrust part of the lower limestone shows considerable disturbances that look like small unconformities (Text-fig. 3). No grooves are seen but there is some shearing below so they are probably minor thrusts. In the quarry 150 feet west of the edge of the reef in one place the lower limestone is bent downwards and sheared into thin slabs like cardboard with traces of broken fossils and stretched aggregates of haematite crystals.

In the quarry at the lower corner of the reef occur clusters of *Liebea hausmanni*, usually found well up in the reef, while in the lower limestone on the top, some years ago, in a part now quarried away I



TEXT-FIG. 3.—Thrusting on the south face of Ford Lime quarry, Claxheugh, a continuation of the upper thrust at Claxheugh Rock. Height of section about 50 feet. R, Middle Shell Limestone reef knoll, at the base are clusters of *Liebea hausmanni*, a bivalve common well up in the Reef. L, Lower Limestone which underlies the reef and becomes divided along the bedding and is partly thrust up and over the reef. At LC are nodules of Chert and at LM it is brown with Manganese. Near the west end it is bent down and sheared into thin slabs. At the top of the section were specimens of *Chonetes woolacotti*, a species found only in the Lower Limestone, confirming that TT is a line of thrusting. BC, Boulder Clay.

collected *Chonetes woolacotti*, a species that is found low down in the lower limestone. This curious thrust of the lower over the middle beds is therefore established on fossil as well as on lithological evidence.

The Permian at Claxheugh is very disturbed; the lower limestone, thrust out in part of the rock face, thickens rapidly southwards. In the quarry the Marl Slate was met with at 75 feet below the bottom. The lower limestone is brown with manganese in patches, and the bedded dolomite has layers and nodules of chert. These are full of structures, Foraminifera, and fragments of Polyzoa which are not seen in the enclosing dolomite.

At the south-west corner of the Ford Lime quarry a few years ago there was a deep excavation in the lower limestone where I collected a number of new fossils, the first that had been found in the Magnesian Limestone since the days of King, Howse, and Kirby nearly 100 years ago. They include *Chonetes woolacotti*, *C. kirkbyi*, a *Camarophoria* like *C. purdoni*, *Pecten sericeus*, and others. Some of them have

affinities with species in the Salt Range, East Germany, or Spitsbergen (Trechmann, 1945).

Half a mile south of Claxheugh Rock were two quarries, now filled in, where the lower part of the reef with its fully developed fauna occurred. At Ford Hall quarry it was in parts more bedded and yielded *Lingula*, *Discina*, and the coral " *Petraia* " *profunda*. The reef knoll passed laterally into cellular calcareous breccia enclosing angular pieces of soft dolomite, the fossils becoming obliterated among the breccia. The brecciation is a chemical segregation rather than a dynamic effect.

Both the upper and lower thrusts seem to have come from a westerly direction; the amount of displacement in the upper can be perceived, that of the lower or main thrust is probably less than the actual length of the rock face.

At the east end a fault brings the highest Coal Measures against the Yellow Sands. This fault is better seen on the north side of the Wear where *Anthracomya phillipsi* occurs. This fault is presumed to be later in date than the Permian thrusting.

A Horizontal Undulating Thrust at the South end of Tunstall Hill Knoll.

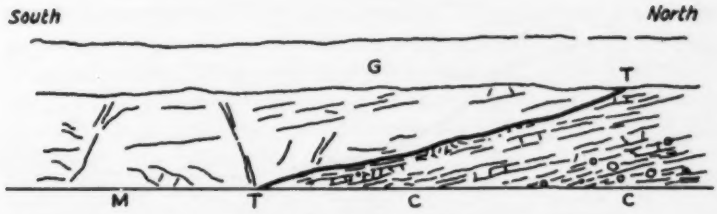
A colliery railway line passes the west side of Tunstall Hill. At the north end is a breccia containing small fragments of structureless chert. Then comes the reef with *Productus horridus* and crinoid stems. South of this, the line cuts through middle breccia, partly bedded, on the flank of the reef. At the south end on the east is an exposure of bedded lower limestone and dolomite lying below the cellular breccia. This is a thrust, but only about 50 yards of it are exposed and one cannot say how far or in which direction it has gone, but it was probably from north to south down the slope of the reef. At the junction is a layer of very soft crushed material, a sort of mylonite. The lower limestone is sheared and broken up in places, it encloses calcareous nodules and cracked and distorted fossils. These include *Camarophoria purdoni*, *Strophalosia lamellosa*, *Lingula credneri*, the two new *Chonetes*, *Fenestella* and echinoderm spines. I found the same fauna in the lower part of the lower limestone in a deep cutting at Claxheugh, so this is the second locality for *Camarophoria purdoni*. It would suggest that a considerable thickness of the lower limestone has been thrust out, but no grooves or striae are seen. The sheared dolomite contains some gypsum in the form of stellar aggregates. It is curious to find a remnant of gypsum here as well as on the Claxheugh thrust plane. It may have survived by being incorporated among the crushed argillaceous mylonitic material.

Displacements along the Escarpment north of the River Wear.

A long quarry at Down Hill shows the middle reef lying on bedded

lower limestone. The junction is sinuous and cuts up and down across the bedding of the rock below, which is broken up at the south end. No grooves are seen, but the under surface of the reef-rock is irregular and coarsely mamillary, and the actual junction shows hackly effects of pressure solution. In the brown reef-rock at the base I found a *Strophalosia* and fronds of *Thamniscus dubius*, a polyzoon that becomes large and conspicuous well up in the reef B or C.

South of this, a smaller quarry exposes Yellow Sands about 40 feet thick, overlain at the south end by Marl Slate and Lower Limestone. Northwards these have been thrust out and the middle reef, a good deal broken up, comes to rest on the Yellow Sand.



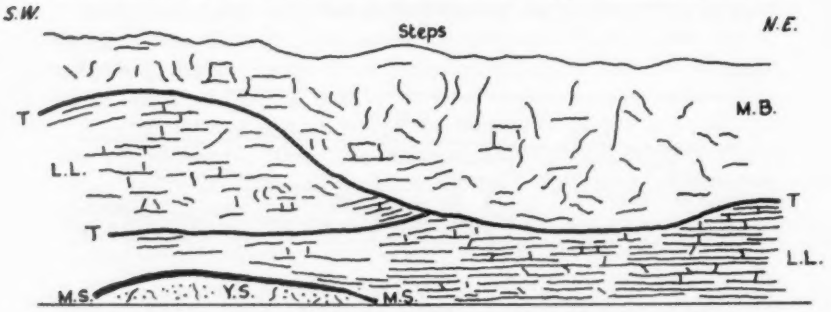
TEXT-FIG. 4.—A thrust in the cliff at the Crags, Hendon, south of Sunderland. Cliff about 30 feet high. Middle are thrust up and over Upper beds. M, Massive middle dolomite, fissured and disturbed in parts. CC, Concretionary Upper beds. TT, Thrust plane, undulating slightly, the concretionary rock below the thrust is sheared. No grooves nor gypsum are seen. G, Glacial beds.

A mile away to the south-east near Hylton Castle, on the lower slope of the escarpment is a quarry in Yellow Sands, almost undisturbed. To the east follows lower limestone dipping a few degrees east, the bedding becomes disturbed and the dip increases to about 50 degrees and the lower limestone looks as if it had been pushed against the reef further to the east. Low down in the lower limestone here I found several *Chonetes woolacotti* in a soft brown dolomite. In the reef one finds *Thamniscus dubius*, *Synocladia virgulacea*, *Pleurophorus costatus*, and *Liebea hausmanni*, but none of the fossil assemblage of the lower part of the reef. It is missing all along the escarpment here and the reef may be 100 feet above its natural base. The pressure that caused these displacements may have come from the west or south-west when the Permian extended to the west of its present position.

The Coast between Ryhope and Sunderland.

At Jean Jiveson's Rock a vertical band about 100 yards wide in the middle Magnesian Limestone has been altered by calcification and silicification. Remnants of the harder parts form a wall-like stack

on the shore. Dr. Woolacott regarded it as part of his system of directional thrusting. Near it on each side the soft bedded dolomite becomes fissured but not moved or faulted, and pieces of the dolomite can be seen unaltered in the breccia. The material forming the rock is calcareous and cherty and clusters of small rose-coloured quartz crystals can be found in it. It has undergone contraction and is slickensided up and down and across, with scratched and smoothed surfaces. No cause is apparent for this local alteration and segregation. Half a mile further north near Hendon in the cliff the middle limestone has been thrust up and over the concretionary upper limestone for a



TEXT-FIG. 5.—Section at Frenchman's Bay, north of Marsden. Cliff about 40 feet high. YS, Yellow Sands. MS, Marl Slate. LL, Lower Limestone. MB, Middle brecciated limestone. TT, Thrust planes.

The middle breccia is thrust over Lower Limestone along an undulating plane. A slice of the Lower has moved over lower limestone, but the Marl Slate and Yellow Sand appear to be undisturbed.

distance of about 30 yards, from south to north. This is another of Dr. Woolacott's major thrust planes, but on the shore at low tide the thrust is much less apparent and seems to die away. Calcification begins along the joints of the massive middle dolomite and a few yards to the north the calcareous layers and ribs become thicker and replace the dolomite and seem to merge into the calcareous concretionary rock. It would seem as if the thrust movement had been facilitated by segregation or replacement of dolomite by calcite. Northwards along the coast the concretionary upper limestone is massive and undisturbed. No grooves or gypsum can be seen, but it is clearly a case of middle thrust over upper beds. The concretionary rock below the thrust has been sheared.

Movements on the Coast between Marsden and South Shields.

Near Marsden Lighthouse a vertical face of concretionary beds is slickensided horizontally in a direction north-east to south-west. No displacement is apparent, but there may have been a to-and-fro

movement with shearing action. South of Marsden Grotto the flexible limestone, the lowest bed of the upper series, is well broken up, the fragments rejoined in places in a sort of dolomitic paste. At the north end of Marsden Bay are Prof. Lebour's breccia gashes, and in some cases these are overlain, as he indicates, by horizontally bedded rock.

At Frenchman's Bay the lower limestone is overlain by thick middle breccia. This is another of Dr. Woolacott's " major thrust planes ". Here in the cliff wedges of the lower limestone have been displaced and thrust over lower. Near the foot of the cement steps at the base of the cliff is an exposure of Yellow Sands and Marl Slate apparently undisturbed in spite of the movements in the lower limestone above it. On the shore the lower limestone is jointed, forming large slabs which are curiously turned up at the joints at angles up to 45 degrees. A broad anticlinal ridge or upward bulge extends out to sea. The shore northwards to Trow Rocks is chiefly lower limestone overlain in the cliffs by middle breccia, but the line of thrusting or dislocation becomes less apparent. The higher part of the lower limestone becomes veined by calcite and brecciated and the lower and the middle seem to merge together.

The thrusting seems to have been activated by alteration and segregation and the distance of movement may be less than might appear. No definite grooves are seen so the direction of the thrust is doubtful. There is a layer of crushed mylonitic marl but apparently no gypsum in it.

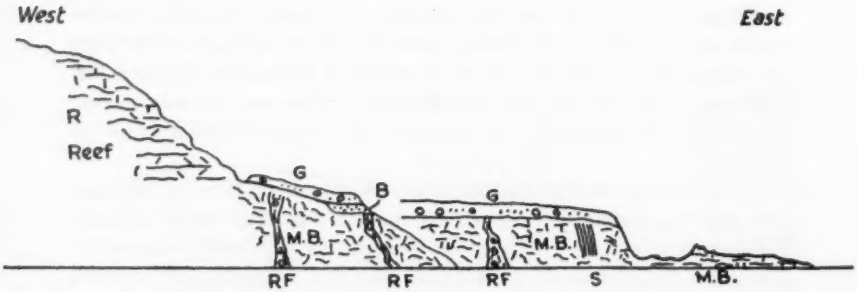
Chourdon Point and Hawthorn Quarry, 7 miles South of Sunderland.

At the north end of Chourdon Point on the coast there is a small anticline of brown bedded dolomite overlain by middle cellular breccia. Dr. Woolacott indicated it as lower limestone, with a question mark, and the junction as a major thrust plane. I was doubtful whether it was lower limestone and later I collected several fossils in it which show it to be a bedded extension of the Shell Limestone Reef B or C. They include *Fenestella*, *Thamniscus*, crinoid stems, *Strophalosia*, *Camarophoria multiplicata*, *Epithyris*, *Cardiomorpha modioliformis*, and *Nautilus*, but no *Productus* or *Spirifer* of the lower part of the reef. Here and at Blackhall Rocks, 5½ miles to the south, are the only places where the shell limestone reef touches the coast. The upper surface is well smoothened and there is a mylonitic layer, but only traces of grooves are visible, which may pass south to north. Some of the fossils are partly silicified and this is the only instance in the Permian where I have seen large fossils becoming chalcedonic. At each side of the exposure the thrusting becomes less apparent and the fossiliferous rock tends to develop calcareous veins and to merge into

the overlying calcareous breccia with powdery dolomite. This thrust is the furthest removed from the main thrusting in the Sunderland area and the distance of movement of the breccia over the hard brown reef rock seems to have been slight. A large quarry up the slope to the west at Hawthorn shows about 80 feet of bedded segregated and calcified rock which merges in places into dolomite with branches of *Thamniscus*, and *Epithyris* and *Bakevellia*, a higher part of the shell limestone Reef C. Nearly all the reef rock in the quarry has been changed to a cavernous crystalline limestone enclosing angular masses of powdery dolomite.

The latest Coastal Uplift and the Easington Raised Beach.

Among the latest movements is the rise of the Shell Limestone



TEXT-FIG. 6.—Section of the shore and lower slopes of Beacon Hill. R, The Shell Limestone reef knoll. MB, Middle brecciated beds on the seaward flank. B, Raised beach at 75 feet altitude. G, Glacial deposits. RF, Fissures filled with red and green Marl and pieces of Upper Magnesian Limestone ; those near to the knoll are crushed and slickensided. S, Vertical slickensides on the rock face.

Knoll of Beacon Hill, north of Easington Colliery. On the breccia that flanks the knoll is a raised beach at 75 feet altitude full of shells and overlain by glacial deposits. It is on a shelf at the inner angle of Shippersea Bay, and at several places along the coast for about a mile at the foot of the knoll the breccia is strongly slickensided in a manner not seen on other parts of the coast. South of the entrance of Hawthorn Dene it is strong and repeated, one face behind the other. Southwards, near Beacon Point there was a cave in the cliff with a remarkable display of red and green marl and lumps of Upper Magnesian Limestone occupying a fissure; the marl crushed and slickensided passed upwards and was bent over towards the knoll. This cave seems to be now buried behind a fall of clay. Below the raised beach is a fissure of red marl moderately crushed and slickensided, while not far away but further from the knoll, a fissure filled with marl and fragments of

concretionary limestone is loose and uncrushed. Further south is another vertically slickensided limestone face on the landward side of a red fissure. The red material is sheared and crushed against the smooth face, but an inch seawards it passes into soft uncrushed marl and the limestone on the seaward side of the fissure is irregular and quite unsmoothened. It looks like a fault with only one face, that on the side of the knoll. The striae are all vertical, but the smooth face is sometimes inclined landwards or seawards or may bulge out towards the sea.

Those sections are informative as regards mode of uplift. The red fissures were filled in during late Tertiary or early Glacial times, they are not seen in the rock on the shore between tide marks, being confined to the cliff towards the knoll. No pieces of the shell limestone of the knoll occur in them, but plenty of the Upper Magnesian Limestone. There has been a general upward urge, the massive knoll has come up and pulled up the middle breccia on its flank with the patch of beach, taking advantage of some of the red fissures as planes of weakness and lubrication.

Meanwhile the shore at Roker or Hartlepool has subsided and taken glacial beds and the submerged forest down with it. The post-glacial sea-shore landscape is in process of becoming exaggerated or regenerated.

Raised beaches are generally found on rocky platforms and are absent from adjacent flat ground, even at lower levels. Waves beating on a shore line have been recorded on earthquake instruments. Such vibrations with the weight of the sea might cause instability and reinforce the upward gravitational pull on a rocky coast. What is high and massive tends to rise while what is low tends to remain where it is or to sink, till deposition and denudation alter the forces.

These striae are not due to falls of the cliff, as was verbally suggested ; fall of parts of the cliff exposes them but they continue back into the cliff where it has not yet fallen away.

Three Borings close together in Crimdon Dene, 6 miles N.W. of Hartlepool.

Three borings were put down in this dene about 1¾ miles from the coast where a stream joins it from the south-west, about 60 feet above sea-level. No. 1, sunk in 1940, was about 200 yards east of No. 2, sunk in July, 1946. No. 3, sunk in February, 1946, was 100 yards north-east of No. 2.

No. 1 went down to 230 feet. Upper Magnesian Limestone persisted to 58 feet, Reef D to 67 feet, Reef C to 190 feet, and Reef B to 230 feet. The latter consisted of yellowish dolomite and the fauna increased in number of species on going down. It was typical reef rock but not

low enough to have *Productus horridus* or the other species common in the lowest part of the reef.

No. 2 was sunk to 253 feet. The upper beds went to 93 feet, and below them came yellow and grey dolomite, more bedded and carbonaceous than the usual reef rock. At 190 feet was a massive dolomite, and at 230 feet a dark fissile dolomitic shale with crushed Polyzoa, coprolitic matter and remains of a Palaeoniscid fish. This bed was very suggestive of the marl slate, and from 220 feet I collected a sample of bedded dolomite an inch thick, strongly contorted and overfolded but with flat layers above and below it, an example of contemporaneous slumping. Below this to 253 feet came dark massive nodular dolomite with hackly bedding surfaces and slickensides containing *Schizodus*, gastropoda, and other fossils.

No. 3. This hole went down to 290 feet. White oolitic dolomite above and hard dense grey bedded dolomite below, to 130 feet apparently represented the upper beds. Below this the middle series consisted of grey and buff bedded dolomites, some parts very hard. At 250 feet were flattened *Strophalosia* in a grey dolomitic shale with pyrites and kaolinite. At 260 feet came massive grey slickensided dolomite with crushed reef fossils including *Productus horridus*, *Epithyris*, *Byssoarca tumida*, and *Schizodus*. At 290 feet was a grey hard dolomite, slickensided with veins of galena, looking rather like lower, but probably still middle limestone.

A good supply of drinking water is obtained from these wells. The unusual facies differences and the slickensiding suggests that at a depth of 300 feet or more there are disturbances that were connected with the removal of soluble constituents and mineralization. The strata exposed at the surface here are not notably disturbed. Reef C occurs east of the railway, west of this are the upper beds, while near Hesleden the highest beds of the reef showing the fauna in its last struggle against adverse conditions, are exposed.

Details of boring No. 1 have already been published (Trechmann, 1941); of the last two there is only space to give the outline here.

Two Borings near West Hartlepool.

At Dalton Piercy 3 miles to the south-west, at 175 feet above O.D., a boring was sunk in 1953, about a third of a mile north of the supposed line of the Seaton Carew fault. There was more than 200 feet of glacial drift, below which came 85 feet of light-coloured dolomite with stellar cavities, and then oolitic and pisolitic dolomite to 300 feet. No fossils were seen, and the rock may be the highest or Hartlepool and Roker beds, or possibly a higher part of the middle beds replacing the shell limestone reef.

Naiseberry, 2½ miles west of West Hartlepool; at 379 feet above

O.D., a boring for water went down to 500 feet. It probably started on middle beds, but at about 218 feet came unbedded reef rock. Fossils including sponge structures, *Fenestella*, *Thamniscus*, *Pseudomonotis*, *Cardiomorpha modioliformis*, *Schizodus truncatus*, *Bakevellia*, and *Pleurotomaria*, about reef C. Below this came a dolomitic pisolite at 230 feet, and at about 440 feet hard bedded apparently lower limestone.

Upper beds only are exposed in the Hartlepool area, but the reef was met with in borings at Howbeck, West Hartlepool Waterworks, and up the slope at Naiseberry. The reef may be 2½ miles wide, but was nowhere pierced to the base, though at Howbeck clusters of *Productus horridus* occur in grey dolomite with kaolin. There is no evidence of the reef in borings south of the Seaton Carew fault.

The Filograna permiana *Horizon.*

Under Sleights in North-East Yorkshire where it is deepest, the base of the Permian may lie at nearly 6,000 feet. A well-marked level is the *Filograna permiana* bed with *Schizodus schlotheimi* and *Liebea septifer*. Below Aislaby, west of Whitby, where potash salts are present, these fossils occur at 4,200 feet depth. The shells are flattened in black shale but the *Filograna* stems are in a matrix of brown fluorite crystals.

Below Billingham this fauna occurs in a limestone associated with the anhydrite bed at about 800 feet depth. It is already some 3,000 feet on its way up. Potash salts are absent, but disturbances, red marl, and anhydrite contorted or rolled together, are seen down the mine. This is attributed to collapse down a buried ridge of Carboniferous rocks (Wood, 1950, p. 335).

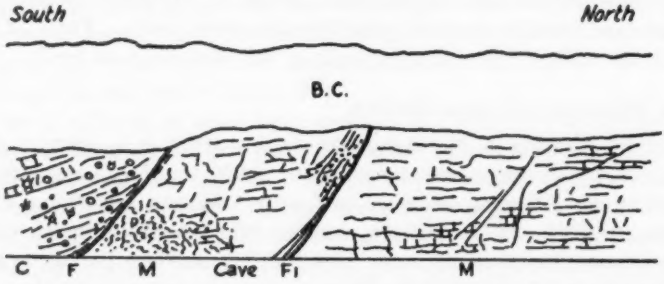
I have been advised to publish my find of these fossils in the cores at Aislaby, and quite recently in the limestone from the Billingham mine.

On the Durham coast from south of Blackhall Rocks northwards to Seaham Harbour the *Filograna* bed is seen at several places down the flank of the Shell Limestone Reef, but not inland. It marks a horizon about the middle of the Upper Magnesian Limestone above the concretionary but lower than the Hartlepool and Roker beds. The *Filograna* rods are separated and lie parallel to one another, but at one place they occur as flattened bundles that branch, suggesting that they are of an algal nature.

The Segregation of Calcite and Dolomite.

In the Magnesian Limestone the calcite and dolomite tend to separate, forming ribs or segregations of impure calcite in a matrix of powdery dolomite. In cores of deep borings where the rock still contains sulphates and chlorides there is no appearance of such separa-

tion. It seems to be a metasomatic process associated with the uplift and removal of soluble constituents and to be peculiar to the Permian. The segregation that has produced the cellular breccia has influenced much of the horizontal movement as well as faulting (Fig. 7). It forms the upper part of the thrust planes at Frenchmans Bay, Tunstall Hill, and Chourdon Point. It affects specially the bedded middle rock on the flanks of the reef but in places the shell limestone reef changes abruptly into cellular calcareous breccia with obliteration of the fossils. In these cases the dolomite seems to have become decomposed. It differs from



TEXT-FIG. 7.—A double fault, half a mile south of Blackhall Rocks. Cliff of Permian 35 feet high; section 100 yards long. C, Concretionary cannon ball series with crushed flexible limestone at the junction; the lower beds of the Upper Magnesian Limestone. M, Middle beds, oolitic dolomite with veins of segregated calcite, unfossiliferous but resting on the Shell limestone reef at Blackhall Rocks. F_1, Fault face seen in a small cave, it is slickensided up and down. The displacement seems to be slight and to have been induced by segregation in the rock.

the Cannon Ball concretionary structure, where the fossils are not destroyed but are sometimes found in the centre or on the surface of the concretions.

Large doubly terminated calcite twins occur in the dolomite of this series near Marsden. The calcite in the Cannon Balls is often distorted and smells of petroleum.

Removal of Sulphates from the Magnesian Limestone.

How and when were the soluble constituents removed from the Durham Permian? In borings nearly a mile deep in North-East Yorkshire the Permian is a dark grey dolomite well charged with anhydrite, gypsum, and salt. Where it underlies the Trias red beds in South Durham at 700–1,000 feet it is still full of sulphates. Gypsum still remains in the red beds at the surface in the Eden Valley and the Midlands. It is not so readily removed by superficial weathering as one might expect from its solubility. Except for the large anhydrite mass 265 feet thick below Hartlepool, the sulphates have been completely

removed from the formation both above and below sea-level. Only remnants of gypsum occur on the face of two thrust planes. Most of the Magnesian Limestone on the Durham coast is still below sea-level and has never been above it. At Blackhall Colliery sinking the base of the Permian was 756 feet below the surface, nearly 700 feet of it still below sea-level. The sulphates seem to have been removed from the area of the formation north of the Seaton Carew fault when the red beds had been denuded and when it was well on its way up, perhaps during the last 1,000 feet of its rise. The cause seems to have been the percolating action of sea water probably under pressure. The Hartlepool anhydrite mass was too large to be completely dissolved away.

Sequence of Movements in the Durham Permian and Possible Causes.

1. Slumping contemporary with deposition.

Thin bedded dolomite, sometimes pisolitic, contorted and faulted near the slope of the Shell Limestone Reef. Contorted dolomite between flat layers in the cores from Crimdon Dene.

2. Displacements during removal of sulphates after commencement of uplift.

Claxheugh rock thrusting. Brecciation and thrusting at Marsden and Tunstall Hill. Probably Eocene and continued in Miocene times.

3. Faulting during further uplift.

Seaton Carew Fault, faults north and south of Blackhall Rocks. Segregation and slickensiding at Jean Jiveson's Rock. Probably Miocene movements.

4. Uplift in Pleistocene times.

Vertically slickensided faces of brecciated limestone involving red marls filling fissures at foot of Beacon Hill on which is the 80 feet interglacial raised beach.

The Claxheugh thrusting is not due to any general shortening of the earth's crust because the Yellow Sands and Marl Slate below, where not thrust out, are undisturbed. These cannot have been replaced by sulphates. The Permian thrusting though on a small scale is difficult to account for because we can point to no uplifted land or submarine slopes down which material might have slid. Remnants of gypsum on two of the horizontal thrusts suggest that it acted as a lubricant. Unaltered beds have been thrust over unaltered, segregated or brecciated over unaltered, but nowhere so far as I know, are unaltered thrust over segregated. The brecciation is not a result of the thrusting, it is a previous calcification effect. Where there is shearing as a result of the thrust it is seen on the surface of the underlying stationary bed. The borings in Crimdon Dene suggest that movements can occur below without a corresponding disturbance of the strata higher up.

As the Permian rose up and some amount, up to a third of its volume, sulphates and evaporites, was removed and calcareous segregation occurred, voids were produced. Some process of gravitational contraction seems to have induced the thrusting movements. These came from different directions, passed up or down and not always on a level or straight course. They did not produce slickensided polished surfaces as on a fault plane.

Upward faulting seems to be due to gravitational pull with mass attraction keeping the surfaces together. Faces of hard rock, partly silicified as at Jean Jiveson's Rock, are smoothened and striated, even where the distance moved is negligible. There is no gypsum on the faulted surfaces.

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(4) On sections in the Lower Permian rocks at Claxheugh. *Trans. Nat. Hist. Soc. of Northumberland and Durham.* New Series, v, pt. 1, 1918. Refers to my description of the anhydrite mass at Hartlepool and gives a photograph of the grooves on the underside of the Shell Limestone at Claxheugh.

(5) The Magnesian Limestone of Durham. *Geol. Mag.*, lvi, 1919, 452–465. Discusses the segregation and possible separation of calcite from dolomite, and contains a photograph of Jean Jiveson's Rock as it then was.

HUDWORTH TOWER,
CASTLE EDEN,
CO. DURHAM.

Alkaline Syenites at Ruri, South Nyanza, Kenya [1]

By William Pulfrey

Abstract

Alkaline syenites from the Ruri Hills in Western Kenya are described, and the hypothesis advanced that their present constitutions have been developed partly by replacement. The syenites occur as dykes and small plugs associated with ring complexes of carbonatites which, together with agglomerates, largely form the hills, and are presumed to be congeneric with an ijolite mass at Usaki.

I. Introduction

THE writer some years ago (1944) gave a brief summary of the geology of an area around the Ruri Hills (Text-fig. 1), near Homa Bay, in South Nyanza province of Western Kenya. The sequence of activity at Miocene volcanic centres, in which prominent carbonatite ring dykes developed, was described. Three kinds of rocks with plutonic aspect were noted in association with the other rocks of the centres—ijolites, feldspathoidal syenites, and a syenodiorite, of which the first have already been described (Pulfrey, 1950). The ijolites, in which no feldspar was detected, occur at Usaki, which is approximately 3 miles north-east of North Ruri, where carbonatites and the volcanic rocks characteristic of the Ruri centres do not appear. The syenodiorite outcrops on the flank of South Ruri and is described here with the feldspathoidal syenites for convenience.

Acknowledgment.—The writer is indebted to Kenya Consolidated Goldfields, Ltd., for the loan of aerial photographs covering the Homa Bay–Ruri area.

II. Field Occurrence of the Syenites

The syenites were noted at five localities, two on North Ruri and the remainder on South Ruri (Text-fig. 1). They comprise:—

(1) The largest, a rather irregular mass, north of the summit of North Ruri, consisting of nepheline syenite, with evidence of some occurrence of basic facies (hybrids ?);

(2) a small mass about three-eighths of a mile south-west of North Ruri spot-height;

(3) the second largest, an inflated dyke-like form, on the west side of the north-eastern ridge of South Ruri in which there is a variety of types including nepheline syenite, nepheline-analcime syenite, analcime syenite, and an apparently non-feldspathoidal syenite;

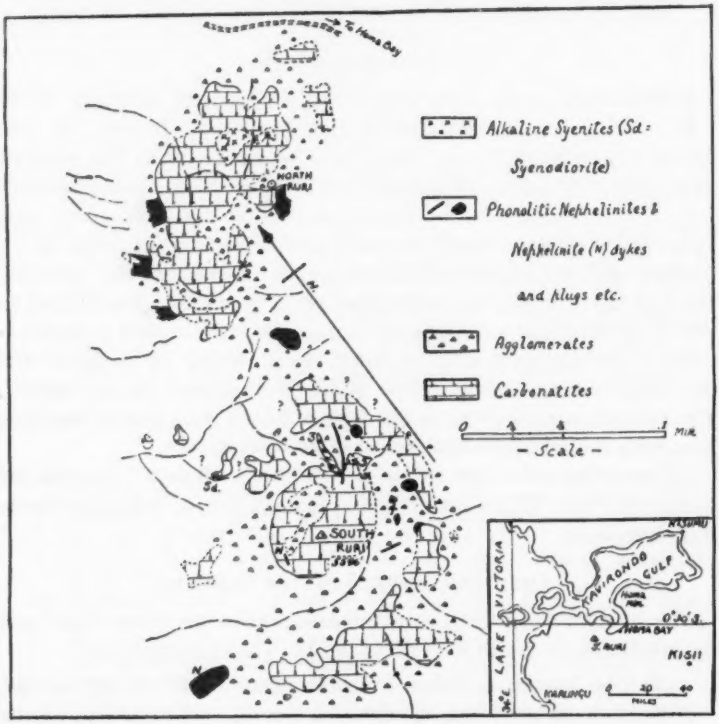
[1] Published by permission of the Commissioner (Mines and Geology), Nairobi, Kenya.

(4) nepheline syenite with prominent vesuvianite, east of the summit of South Ruri;

(5) " nepheline " syenite on the east slope below the phonolitic nephelinite dyke forming the north-east ridge of South Ruri;

(6) syenodiorite on the north-western flank of South Ruri.

The North Ruri syenite (1) is emplaced in carbonatites of the main phase (Pulfrey, 1950, p. 426), and is probably a partial ring



TEXT-FIG. 1.—Alkaline syenites and carbonatites of the Ruri Hills, near Homa Bay.

dyke around the northern of the two centres that make up North Ruri. The extent of the outcrop shown on the map is based largely on the work of B. N. Temperley who, when a member of the Geological Survey of Kenya, visited the area recently. The syenite is in the writer's opinion surrounded by carbonatite, but it has not been proved whether it is intrusive, or whether it is a relic of an earlier larger mass engulfed by the carbonatite.

The small mass (2) on the southern flank of North Ruri invades

carbonatite high up on the hills, and as it is more easily eroded than the limestone has allowed the formation of a small cave.

The dyke-like mass on South Ruri (3) is largely emplaced in agglomerate, but at its southern end is seen to invade the main carbonatite and is cut off by the nephelinite dyke that forms the long northern ridge of South Ruri. Around the southern end of the mass a small area in which the contact carbonatites have become enriched in apatite was discovered. The maximum P_2O_5 content determined was 12·0 per cent, corresponding with 29·3 per cent of fluor-apatite.

East of the summit of South Ruri the small intrusion (4) is emplaced generally within agglomerates, but is close to a small body of carbonatite, not shown on Text-fig. 1, and is itself intermingled with carbonatite. Other small masses (5) on the east side of South Ruri invade carbonatite of the main phase, but are themselves cut by late narrow carbonatite veinlets. The main limestone has, as on the western side of the hill, been notably enriched in apatite which, in the field, frequently appears as yellow crystals or clusters protruding from the surface.

The shape and relations of the syenodiorite which, as will be seen, contrasts in several ways with the feldspathoidal syenites, are obscure. It was found as blocks "outside" low cliffs of carbonatite of an outer ring of the South Ruri centre. In the field it was regarded as a lava, but thin sections indicate that it is a hypabyssal type.

III. Petrography of the Syenites

1. *North Ruri*

Three specimens of the North Ruri syenite have been examined in detail, two of nepheline syenite (juvite type) (IV/108 and 110 [1]), and one a melanocratic aegirine syenite (IV/109). Both the nepheline syenites might be called porphyries in so far as they have large phenocrysts of various minerals and a rather sparse much-altered matrix of much smaller crystals. They are composed predominantly of nepheline, orthoclase, and aegirine-diopside with accessory augite, sphene, apatite, and pseudomorphs of an unidentified mineral, and late replacements of cancrinite and calcite; specimen IV/110 also contains occasional small patches and veinlets of analcime.

The orthoclase is present in platy poikilitic crystals, often exhibiting Carlsbad twinning, that range up to 18 mm. in length in specimen IV/110. The optic axial angle is large and no sign of fine twinning was seen. All contain numerous chadacrysts of nepheline (Text-fig. 2*c*), and often of aegirine-diopside and calcite. The nepheline also occurs as crystals separate from the orthoclases, sometimes up to 1·5 mm. diameter, and as chadacrysts in the dark outer zones of some of the

[1] Numbers prefixed by IV refer to specimens in the collections of the Geological Survey of Kenya.

pyroxene crystals. It is always idiomorphic, and occasionally zoned by secondary products. Replacement by cancrinite and calcite is variable: some crystals are untouched, and there is every gradation to complete alteration. Some of the nepheline encloses spiky crystals of pyroxene.

The pyroxenes include grey or slightly mauve-grey augite, with extinction angle Z ∧ c 52°, as occasional cores in the more common aegirine-diopside [1] which forms the bulk of the pyroxene. The aegirine-diopside is fairly common and often occurs with prismatic form, ranging up to about 1·5 mm. length. The crystals have strong colour and usually a more deeply coloured outer zone. Occasionally small crystals are skeletal (Text-fig. 2*e*) due to growth among already crystallized nepheline crystals. In specimen IV/110 crystals of pyroxene tend to cluster on the faces of larger nepheline crystals and sometimes on the orthoclases. In addition to the colour-zoning, where the outer zone has assumed a composition closer to aegirine than the core, occasional crystals are multiple-zoned as indicated by variable extinction angles in different parts, but without noticeable variation in colour. The pleochroic schemes of the colour zones are:—

Cores . . X strong bright green, Y yellow green, Z yellow.
Outer zones . X dark green, Y strong green or bluish-green, Z yellow.

The maximum extinction angles measured were—cores Z ∧ c 69½°, outer zones X ∧ c 16°.

Sphene occurs as scattered sphenoids up to 1·1 mm. length in specimen IV/108, but is much smaller (up to 0·2 mm.) and often irregular in IV/110. In the former it is slightly pinkish grey and feebly pleochroic. Apatite is not common, though it occasionally occurs in rather large crystals (e.g. 0·35 × 0·2 mm. in IV/108). In slide IV/108 one grain shows replacement by orthoclase along a crack. None was seen in nepheline. The unidentified mineral is now represented by prismatic pseudomorphs in calcite or calcite sprinkled with iron oxides. They are usually small but on occasion attain a length of 1·5 mm., and apparently all lie within the feldspars, though it is possible that others are undetected in the much altered "matrix". In some, partings or cracks, almost at right-angles to the length, can be seen. The pseudomorphs may represent original wollastonite.

Cancrinite replaces nepheline and occasionaly orthoclase, and occurs in patches in the "matrix" and in veinlets associated with calcite. Calcite is less common and occurs in irregular patches, some of which are interstitial, and as rhombs in the orthoclases.

The aegirine syenite (IV/109) is of totally different type. Its relation to the nepheline syenites is unknown, but it may be a hybrid marginal

[1] The predominant pyroxene is called aegirine-diopside on analogy with the pyroxenes of the near-by Usaki ijolite.

type or possibly a melanocratic fenite. The hand-specimen is green and fine-grained with occasional whitish streaks; in thin section it is seen to be partly crystalloblastic with irregular distribution of its minerals, parts having abundant pyroxene and others being almost free of it. Orthoclase forms a base and occasionally occurs in coarse prisms and plates. Two pyroxenes are present, scant small crystals of aegirine-diopside, and abundant needly crystals of aegirine. The aegirine-diopside ranges up to 1·25 mm. in length and is often heavily mantled with aegirine. It has extinction Z ∧ c 77° and is pleochroic X medium green, Z yellowish. The aegirine occurs mainly as criss-crossing needles up to 0·75 mm. in length, though usually much less, and has extinction X ∧ c 4° and pleochroism X dark green, Y green, Z yellow. Some needles are grown in parallel manner with radiate calcite fibres. Apatite occurs in sporadic small grains and aggregates, and locally many small crystals lie within feldspars. Analysis showed that the rock contains 1·24 per cent P_2O_5. Calcite is abundant, largely as irregular replacive patches, but also clear and interstitial to feldspars, and as radiate needly pseudomorphs that may represent original wollastonite. Natrolite is present as fine-grained mosaics, but no evidence was seen to suggest that it has been derived from nepheline.

2. *South Ruri*

The large dyke-like mass on South Ruri varies considerably from exposure to exposure. One specimen collected (IV/168, a fallen block) is a cancrinitic nepheline syenite. It is a medium-grained mottled grey rock in which nepheline and pyroxene are idiomorphic. Orthoclase acts as a coarse base to the whole. Cancrinite forms common large irregular patches partly replacing nepheline or is developed along cracks, though sometimes it is interstitial and apparently primary. Calcite is also not uncommon. The pyroxene, in crystals up to 1·5 mm. across, is aegirine-diopside with extinction Z ∧ c 72° and pleochroism X light green, Y yellow green, Z yellow. Occasionally trains of small crystals of the pyroxene are seen running through the feldspar (Text-fig. 2*a*), and rare crystals are almost skeletal in outline, having grown among nepheline crystals now replaced by cancrinite. The pyroxene is often intergrown with a reddish-brown, presumably titaniferous, biotite which, however, is present in considerably less proportion than the aegirine-diopside. It occurs in crystals up to 1 mm. across and is sensibly uniaxial. Accessory minerals are represented by sphene and apatite. The sphene is fairly common and occasionally large, e.g. 1·3 mm. in length. Apatite occurs in prisms and irregular grains, one aggregate being 1·3 mm. across; it is not, however, an abundant constituent, chemical analysis indicating 0·44 per cent P_2O_5. Some grains in feldspars are notably corroded: there is

apparently none in the nephelines. Zeolites are represented by natrolite replacing nepheline and in small patches associated with cancrinite. Analcime is also present, as patches associated with the zeolite and calcite.

TEXT-FIG. 2.—Structures in alkaline syenites at Ruri. The bar scale in each case represents 0·1 mm. (*a*) IV/168. " Seed " pyroxenes replacing orthoclase (coarse stipple = calcite). The group of small pyroxenes lies within one orthoclase crystal. (*b*) IV/171. Nephelines poikilitically enclosed in pyroxene. (*c*) IV/110. Nepheline and pyroxene chadacrysts in orthoclase (coarse stipple = calcite). (*d*) IV/108. Orthoclase replacing apatite (coarse stipple). (*e*) IV/108. Skeletal pyroxene interstitial to nepheline crystals. (*f*) IV/168. Skeletal pyroxene in a nepheline largely replaced by cancrinite. The pyroxene is mainly in contact with the latter. (*g*) and (*h*) IV/173. Poikilitic hornblendes enclosing feldspar. (*j*) IV/173. Partial replacement of microcline by hornblende.

The second type is a nepheline-analcime syenite (IV/171). It is medium-grained, mottled black and white, with irregular distribution of the dark minerals. Joints are filmed by calcite. Much of the light components has been replaced by secondary minerals, but a small amount of clear orthoclase remains. Nepheline is more abundant in idiomorphs up to ½ mm. across, but all are somewhat corroded by the secondary products. Pyroxene is abundant and often large, up to 2·6 mm. in length. It is aegirine-diopside with extinction Z ∧ c 74° and pleochroism X bright green, Y yellowish green, Z brownish yellow. It is mostly irregular and sometimes of fantastic shape, though occasionally sub-idiomorphic; some is poikilitic, enclosing numerous nephelines (Text-fig. 2*b*). Accessories are sphene, apatite, and magnetite. The sphene occurs in scattered grey sphenoids up to 0·6 mm. in length that in some cases appear to be corroded by the pyroxene. Apatite is not uncommon (chemical analysis of the rock showed 1·50 per cent P_2O_5) in irregular aggregates, one being 1·7 × 0·8 mm. It is occasionally enclosed in sphene, but most is closely associated with pyroxene and appears to be late in the paragenesis. Magnetite, mostly oxidized, forms rare grains up to 0·5 mm. across; more is present as fine grains within pyroxene crystals, where it may represent a released mineral. Calcite occurs as occasional patches. Analcime is present in considerable amount and forms a matrix to the other minerals and large pools. It is sometimes intergrown with cancrinite, which also sporadically replaces nepheline. The latter is also replaced in places by a fibrous zeolite.

A second variety of nepheline-analcime syenite (IV/191), enclosing a xenolith of green lava, was found at the eastern tip of the intrusion where it is capped by carbonatite and close to the long N–S phonolitic nephelinite dyke. The syenite is rich in carbonate (often iron-stained, though some is clear and resembles calcite) some of which is interstitial, though much is clearly replacive. Orthoclase is plentiful in long crystals up to 3 mm., often orientated in a common direction. Little nepheline is present, and what there is is in small crystals usually surrounded by analcime, occasionally with an intervening cancrinite sheath. The pyroxene, often in long prisms, is a dark green aegirine. There are also carbonate pseudomorphs of an unidentified prismatic mineral. Analcime occurs as patches, often enclosing shreds of carbonate and cancrinite. Zeolites are rare, and apatite and sphene are accessory.

A third type (IV/169) is an analcime syenite in which nepheline, cancrinite, and apatite were not identified. The principal component is anorthoclase, in prisms and plates up to 2¼ mm. in length, of which the margins are often irregular owing to penetration by pyroxene crystals. The pyroxene, which is a dark green aegirine, occurs as

slender prisms up to 1 mm. in length, often aggregated in radial sheaves. There are also large (1½ mm.) apparently prismatic crystals of an unidentified mineral now pseudomorphosed by aggregates of iron-stained calcite, occasionally associated with a zeolite. They may represent original wollastonite. In a slide of a generally similar though more leucocratic rock (IV/170), however, the pseudomorphs are obviously interstitial, and they may possibly represent original iron-rich carbonates. Calcite is also not uncommon as clear interstitial patches and replacing feldspar. Analcime forms irregular patches which in places can be seen to corrode the feldspar. Zeolite, mainly natrolite, forms finely granular aggregates lying interstitially to the feldspars. The only accessory noted was sphene, in small aggregates and minute colourless or yellowish crystals.

The small intrusion south-west of the eastern peak of South Ruri (a cone of phonolitic nephelinite) is a nepheline-vesuvianite syenite (IV/138). Its feldspar is orthoclase, which in places encloses small idiomorphic nephelines. Other nephelines, up to 1·5 mm. across, occur in the matrix, some being enclosed in cancrinite. Some is unaltered, but much is zeolitized or partly replaced by cancrinite. The pyroxene is a dark slightly bluish-green aegirine-diopside with extinction X $\wedge$ c 16½°, that has moulded itself on the feldspars and nephelines. Pseudomorphs of an unidentified mineral are as frequent as the pyroxene, with which they sometimes interfinger. They are grey or brownish and often of streaky appearance, and now consist of carbonate-iron oxide aggregates. They may represent original biotite comparable with that described from the syenite (IV/168) west of the large dyke. The vesuvianite, which is quite common, occurs in generally colourless idiomorphic or sub-idiomorphic uniaxial negative crystals up to 0·75 mm. in length. Occasional crystals appear slightly resorbed. A few octagonal basal sections can be seen in the slides, but cleavages are rarely visible. One crystal has pleochroism from faint pink to colourless, and rare crystals enclose apatite or pyroxene prisms or small nephelines. In other cases the vesuvianite appears to have developed before the pyroxene, unlike the paragenesis described by Phemister (1926) at Loch Ailsh. There is also a marked difference from the order of crystallization described by Quensel (1914, p. 173) for the vesuvianite-bearing canadites at Almunge, in which vesuvianite appears to precede nepheline and feldspar. Accessory minerals include apatite, sphene, analcime, cancrinite, and calcite. The apatites are often long and slender and readily distinguished from the much stouter vesuvianites. Sphene is present as sparse yellow crystals. Analcime occurs as small and occasionally large interstitial patches, some of which enclose shreds of calcite. The cancrinite occurs as interstitial and poikilitic patches and appears to be an original constituent.

Calcite, in addition to forming the larger part of the unidentified pseudomorphs, is present also as small irregular patches replacing other minerals.

The syenite (IV/218) at the head of the valley draining the eastern slope of South Ruri, where two small masses were mapped, is of different type. It is a green apparently rather fine-grained rock, enclosing feldspars up to 3 mm. in length, which are whitish on weathered surfaces. The feldpsar is orthoclase and, in addition to the prismatic crystals, forms a coarse allotriomorphic base through which abundant fresh green needles, prisms, and radiate aggregates of aegirine are scattered. Scattered patches of carbonate are fairly common and zeolite, probably natrolite, is abundant. Much of the zeolite pseudomorphoses small nephelines and possibly sometimes feldspars, but some is interstitial to unaltered feldspars and may represent an original crystallization product. Small patches of analcime are associated with the zeolite.

The remaining intrusion, from the lower north-west flank of South Ruri, is a hornblende syenodiorite (IV/173), apparently unrelated to the syenites described above. It is a dark grey highly porphyritic rock that in thin section is seen to have a coarse hypidiomorphic texture. Oligoclase forms large, often zoned, crystals (up to 4·5 mm.) and there are also crystals of microcline which are abundantly replaced by spindles and plates of hornblende (Text-fig. 2*j*). Microcline also occurs interstitially accompanied by orthoclase, some of which is microperthitic. Rare small patches of quartz are associated with the feldspar and in one case quartz forms irregular grains along twin planes. The ferromagnesian minerals are hornblende and biotite. The hornblende is plentiful and often idiomorphic in twinned crystals up to 2 mm. length, though it also occurs as needly aggregates and interstitially among the smaller feldspars. Some of the larger crystals are seen in fact to be aggregates of needly crystals. Others are extensively sieved (Text-fig. 2*g*, *h*) enclosing feldspar, representing various stages in the replacement of aggregates of feldspar grains. In other cases the hornblende is moulded on feldspar, though it has penetrated into them along cracks. The hornblende is pleochroic: X grey, Y green, Z light green, with extinction $Z \wedge c$ 25°. Biotite is present as dark reddish brown crystals dichroic to pale biscuit, the crystals being usually small but occasionally as much as 1·5 mm. across. The only accessory noted was apatite in small prisms.

IV. Petrogenesis

The crystallization of the syenites followed an agpaitic mode in its early stages. The determination of the order of crystallization is not

simple, but from consideration of all available conclusions it appears that the paragenesis in the nepheline-bearing types is:—

nepheline—orthoclase—sphene—{ aegirine-diopside / aegirine / (vesuvianite) } —

(biotite)—{ calcite / cancrinite / analcime } —needly aegirine—zeolites.

The terms in parenthesis appear only in one rock each of the group. Apatite appears to have crystallized throughout the early felsic stages. The relation of augite to the felsic minerals cannot be determined as it is always sheathed by aegirine-diopside. In some cases, as in specimen IV/110, there are two generations of aegirine-diopside, an apparently earlier generation being represented by small idiomorphic crystals enclosed in orthoclases, though it appears that in some cases such crystals have grown by penetration along cracks. The lack of melanite is notable and only in one case was vesuvianite, which might be considered as derived by assimilation of carbonatite, observed. No wollastonite was found though in some cases the unidentified pseudomorphs may represent it.

The parageneses bears a strong resemblance to those determined for the ijolites at Usaki. They differ notably, however, from those established by von Eckermann (1948, p. 47) for alkaline syenites at Alnö, in which in one case melanite and pyroxene precede the felsic minerals, and in the second case though nepheline is the first mineral to crystallize it is followed by pyroxene, and not by feldspar.

In the nepheline-free types the succession is generally similar, viz.:—

apatite—orthoclase—aegirine-diopside—{ calcite / analcime } —
needly aegirine—zeolites.

Numerous replacement structures can be detected among the various minerals (Text-fig. 2), and assist in the assignment of their relative ages. Interstitial and poikilitic textures, and the grouping of a mineral around an earlier one with some replacement, as for example pyroxene around orthoclase, are equally valuable. It appears, as in the ijolites of Usaki (Pulfrey, 1950, p. 443), that the pyroxenes are always late minerals and probably largely emplaced by replacement. It is a significant fact that nephelines enclosed in the pyroxenes are frequently corroded, whereas those enclosed in orthoclase are sharply defined and idiomorphic. This suggests that the nepheline-orthoclase relationship is one of normal enclosure of already formed crystals in a subsequently crystallizing mineral, pyroxene and other later minerals being formed by infilling and replacement. This in turn indicates that the rock originally emplaced was probably much more felsic than those now seen. It is postulated that the later changes

were brought about by the passage of magmatic fluids through the completely consolidated rocks, in a manner analogous to that suggested by Lehmann (1951) in his process of allopegmagenesis, or by Collomb (1952) for the formation of large feldspars. That such fluids were operative is indicated by the impregnation of the wall-rocks with apatite, especially on south-western Ruri. The reactions that such fluids caused in ijolitic masses at Usaki, and probably in similar intrusions at lower levels at Ruri, have already been indicated (Pulfrey, 1950, p. 447). The original products at Ruri were, however, probably of pulaskitic type, rather than urțitic. The intrusions occur late in the volcanic sequence (Pulfrey, 1944, p. 102), and it is probable that any magmatic materials then available may have changed their composition as compared with that available earlier, by incorporation of wall material at depth. Lavas, however, that followed the syenite were similar to earlier flows in the sequence, so that if such modification had taken place it must have been local. The source of the feldspar is perhaps to be sought in the fenitizing effect of fluids passing from ijolitic masses, mobilization of the fenites having occurred in the later stages of the lives of the volcanoes in the manner postulated by von Eckermann for Alno (1948, p. 161). It is perhaps important in this connection that the syenites are small bodies, sometimes highly irregular, and emplaced at much higher levels in the volcanic piles than the ijolites.

It is assumed that during the passage of such feldspathic fluids through the carbonatites desilication took place, leading to the formation of nepheline. Such a process explains the frequency of the occurrence of orthoclase in the syenites, and not soda-orthocase or anorthoclase. During the interactions of the fluids the opportunity would arise for the formation of such minerals as vesuvianite, wollastonite, sphene, and cancrinite.

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Solution Subsidence Outliers of Millstone Grit on the Carboniferous Limestone of the North Crop of the South Wales Coalfield

By Trevor M. Thomas

Abstract

A record has been made of the outliers of Basal Grit occurring on the Limestone of the North Crop of the South Wales Coalfield, some of which have not previously been located. The solution subsidence theory to account for their present anomalous levels when compared with the parent Grit outcrop to the south has been enlarged upon, and an attempt has been made to determine the mechanism of this subsidence which ranges in vertical extent up to a maximum of approximately 600 feet. The outliers are of economic importance since their predominant crumbly quartzose sandstones are a source of almost pure silica sand.

Introduction

In the portion of the outcrop of Carboniferous Limestone and Millstone Grit east of the River Twrch, it has been calculated that more than 10,000 acres have been closely pitted by circular swallow holes ranging up to 100 yards in diameter and 60 feet in depth. On the Millstone Grit it was found that the most southerly located swallow holes overlie approximately 250 feet of Grit beds so that a slightly higher figure than this probably represents the maximum vertical spread of solution subsidence between these surface manifestations and the initiating caverns in the Carboniferous Limestone directly below.

A survey of the several outliers of Basal Grit overlapping the Limestone outcrop to horizons as low as the topmost beds of the Cleistopora Zone has revealed solution subsidence of a greater order which has given rise to a vertical displacement of Grit beds up to a maximum of about 600 feet. Remnants of a former Grit cover have thus been preserved up to this depth below their original position and without great modification other than inconsistency of dips over short distances. Bedding planes are normally still discernible whilst the lithological characteristics of the constituents of these outliers are identical with those of the parent Grit outcrop, the only measurable difference being the preponderance of rotten quartzose rock produced by the loss of siliceous cement. In these respects the outliers contrast with the smaller but deeper pockets of silica sands, siliceous clays and pebbles filling pipes in the Carboniferous Limestone of Derbyshire (*Special Reports on the Mineral Resources of Great Britain*, Vol. vi, 1918, p. 164). Allied to the latter but on a more intricate though less spectacular scale are the vertical, oblique, and horizontal pipes, infilled with

water-transported Eocene sand, occurring within the Chalk of Hertfordshire, well below the Tertiary-Chalk junction (Kirkaldy, 1951, p. 219). The gash breccias exposed in the Carboniferous Limestone cliff sections of south Pembrokeshire illustrate solution subsidence phenomena of a scale approaching these Millstone Grit outliers, but differ in that the original cavern collapses entailed preservation of blocks of the overlying roof limestone (later cemented by red clay or stalagmite) rather than a later formation capping (Dixon, 1921, p. 161).

The Grit outliers vary greatly in size, but the majority have axial lengths ranging from 150 to 300 yards. So far as can be determined their cross profiles are in the form of shallow basins, locally irregular, with minor pits and pinnacles contained within the main units. Although the central areas of none of the larger outliers have been bottomed it is unlikely that even in the largest outlier, with a length of 400 yards, the maximum thickness of the Grit exceeds 100 feet. The location of practically all these outliers on the floors of transverse valleys or gaps marking a recession or diminution in the Limestone escarpment suggests that solution subsidence on a larger scale than is now evident has played a part in determining the present drainage or valley pattern of the Limestone outcrop. Examples of such valley courses arising out of linear solution collapses have been described from America (e.g. Fridley, 1939).

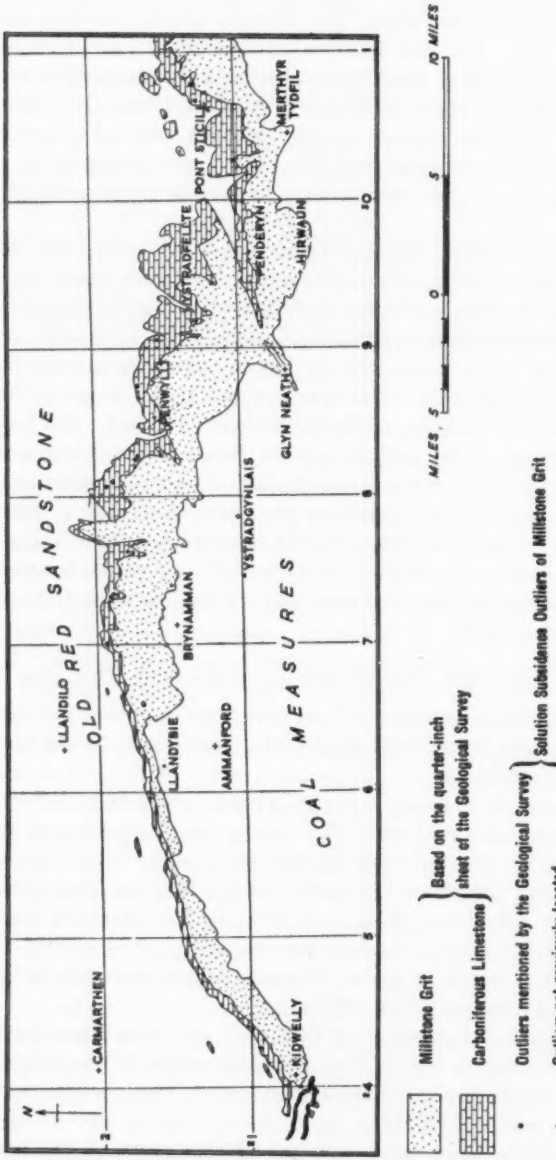
Location and Extent of Individual Outliers

Some fourteen separate outliers have been determined to date, eight of which have been briefly described or mentioned by the Geological Survey (Text-fig. 1).

Beginning in the east, Cefn yr Ystrad, north-east of Pont Sticill, shows two such outliers. The larger, sited immediately north of Twynau Gwynion (Grid Ref. 32/082128), is in the form of a low mound with an axial length of 150 yards and has been let down some 30 to 50 feet by subsidence (Robertson 1933, p. 36). About a mile to the west (069127) a silica sand-pit has worked a small outlier of rotten Grit, with a length of about 40 yards, which has been subjected to subsidence totalling 400 to 500 feet.

North-east of the village of Penwyllt, and immediately east of the prominent swallow hole of Pwll Byfre, an outlier of Basal Grit located near the northern edge of the Limestone has been extensively worked for silica sand (22/876167).

West of the Tawe valley and immediately north of the Basal Grit bluff of Castell y Geifr (827168) two elliptical mounds, separated by a peat bog, are composed of Grit beds which have been let down by subsidence to the extent of a maximum of 200 to 300 feet. Lack of



TEXT-FIG. 1.—Generalized map showing the location of solution subsidence outliers of Millstone Grit on the Carboniferous Limestone of the North Crop of the South Wales Coalfield.

suitable exposures and the great abundance of grit blocks in the surrounding drift render accurate definition of these outlying masses of Grit impossible. These could be mapped as two outliers or merely as a slumped northward appendage to the main Grit outcrop; the nature of the surface configuration favours the first interpretation.

Two more outliers are located near the lower course of the River Giedd and north of Sink y Giedd, the swallow hole marking the commencement of its subterranean course. At two points on the extremities of adjoining meanders of this stream and a third of a mile inside the Limestone outcrop (813184 and 812183) recent lateral erosion or undercutting of the 20 to 30 feet high banks has brought to light good exposures of Grit. These sections probably form part of the same outlier with an estimated length of 300 yards. Subsidence to the vertical extent of 300 to 400 feet is the only satisfactory explanation for its present anomalous level. The second outlier lies a third of a mile to the north-west (809186), in the form of an elongated mound with a length of approximately 200 yards, and is attributable to subsidence amounting to about 400 feet (Robertson, 1933, p. 60).

Three miles to the west two outliers with lengths of 350 yards and 200 yards, widths of 150 yards and separated from each other by a peaty tract about 250 yards long, are sited on the floor of the well-defined valley formed by Nant Llynfell, a right bank tributary of the Twrch. The more northerly of these two outliers (765176) owes its present position and preservation to subsidence of 300 to 400 feet whilst in the southern outlier (762173) subsidence was in the order of 200 to 300 feet.

On either side of the Brynamman–Llangatock road, where it traverses the crest line of Black Mountain, outlying rotten Basal Grit beds overlapping the Limestone outcrop have been periodically worked as a source of silica sand for well over half a century. Two small outliers have been worked to the east of this road (733186 and 733184), but these are overshadowed by the scale of workings to the west of the road which have determined the existence here of the biggest solution subsidence outlier of Millstone Grit yet discovered. This has a maximum estimated length and width of 400 and 200 yards respectively Some of the beds constituting this outlier now lie up to 400 to 500 feet below their original position.

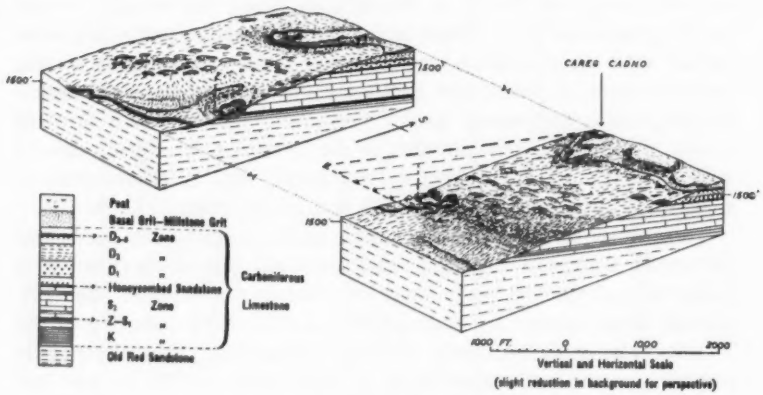
Two miles to the west of this, recent erosion of the banks of the north-north-westerly directed main headstream of Afon Cennen has revealed the existence of a bedded outlier of Millstone Grit overlying a comparatively low horizon of the Upper Seminula Zone (S_2) (702193). This outlier has an estimated length of 150 yards and involves subsidence of the order of 400 feet.

On the northern slopes of Mynydd y Gareg, to the north-east of

Kidwelly, Millstone Grit debris, overlain by Glacial drift and probably let down more than 400 feet by subsidence, fills a close group of swallow holes well inside the Limestone outcrop (428089) (Strahan, 1909, p. 85).

Details of a Typical Outlier

The outlier near Pwll Byfre, north-east of the village of Penwyllt, has been selected as a typical representative for fuller description (Text-fig. 2). Here the field evidence suggests a maximum diameter



Text-fig. 2.—Simplified block diagrams illustrating the relationship of the Millstone Grit outlier near Pwll Byfre (1½ miles north-east of Penwyllt) to the Basal Grit outcrop on Careg Cadno (zonal subdivision of Carboniferous Limestone based on T. Robertson, 1932).

of about 250 yards. Its position in relation to the parent Basal Grit, now one-third of a mile to the south on Careg Cadno, indicates a maximum vertical subsidence of 500 to 600 feet. Since the cessation of silica sand workings on this outlier, slumping has tended to obscure the clarity of the working-face sections, but certain details can still be determined. Irregular extraction areas show a maximum depth of 45 feet, the bottom of the deposit not being reached. Massive well-jointed quartzose sandstones, rotten and often very friable, are the most typical rock members. A 3- to 4-foot band of fine-grained soft flaky siltstone, normally grey-white, but with some red staining, is conspicuous towards the northern edge of the outlier. In places the massive quartzose beds become conglomeratic with quartz pebbles ranging up to 2 inches in diameter whilst at other points the more prominent beds are harder and quartzitic in type showing fine banding. Dips are variable and difficult to assess, both because of the lenticular form of

many of the beds and the broken and jumbled nature of the deposit. In some sectors an east-south-eastward dip of 70° to 75° can be made out through successions up to 25 feet thick. Elsewhere the present lie of the banding in blocks of quartzitic sandstone indicates overturning and up-ending.

The site of this outlier is coincident with a slight southward recession of the Limestone escarpment giving a basin-like effect. A distinctive mounding is very much in evidence, its eastward termination being marked by a general fall in level of 10 to 15 feet whilst to the west the adjoining Limestone outcrop is at a lower level to the extent of up to 10 feet.

Conclusions

A lowering of surface by solution subsidence has been proceeding more or less continuously since Triassic times on this high moorland terrain. The bulk of the outliers possibly date from mid-Tertiary times although they have in all probability been subjected to further movement since then.

The location of some of these outliers at points up to half a mile inside the Limestone outcrop is itself a measure of the rate of southward recession of the Basal Grit capping. Present dips of the beds constituting the outliers suggest that the latter were initiated by large swallow holes perhaps 30 to 60 yards in diameter and 25 to 60 feet deep pocking an original Basal Grit cover of 40 to 100 feet. The initial collapses of the Grit beds were sharp and gave rise to vertical displacements of individual beds up to a maximum of approximately 60 feet. The latter figure represents a small part of the 600 feet, estimated as the greatest vertical displacement, but it is thought that although subsequent movements were individually slight they were spread over a great period of time so as to have a considerable cumulative effect. A series of further collapses of the initial intensity would surely destroy all traces of the original bedding and so give rise to an accumulation of jumbled blocks perhaps cemented together to form a "boulder" breccia as in the case of the Triassic gash breccias of south Pembrokeshire.

On this view, the large outliers represent a number of closely-adjoining cavern infillings (initiated by large and deep swallow holes) which along with the formerly contiguous or enveloping Grit beds were later subjected to long drawn-out but less sharp subsidence. The smaller outliers are either eroded remnants of the deeper segments of large outliers or are merely "fossilized" swallow holes produced by a continual concentration of subsidence at a single point rather than over a wider area. Irregular scatterings or trains of Grit blocks, where

these have no obvious Glacial or gravity interpretation of origin, might be the remnants of outliers of either category.

The writer wishes to thank Dr. F. J. North, Keeper of the Geological Department, National Museum of Wales, for reading the manuscript of this paper.

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"TY DERW,"
ELY VALLEY ROAD,
TALBOT GREEN,
LLANTRISANT,
GLAM.

The Silurian Succession at Gorsley (Herefordshire)

By J. D. Lawson

Abstract

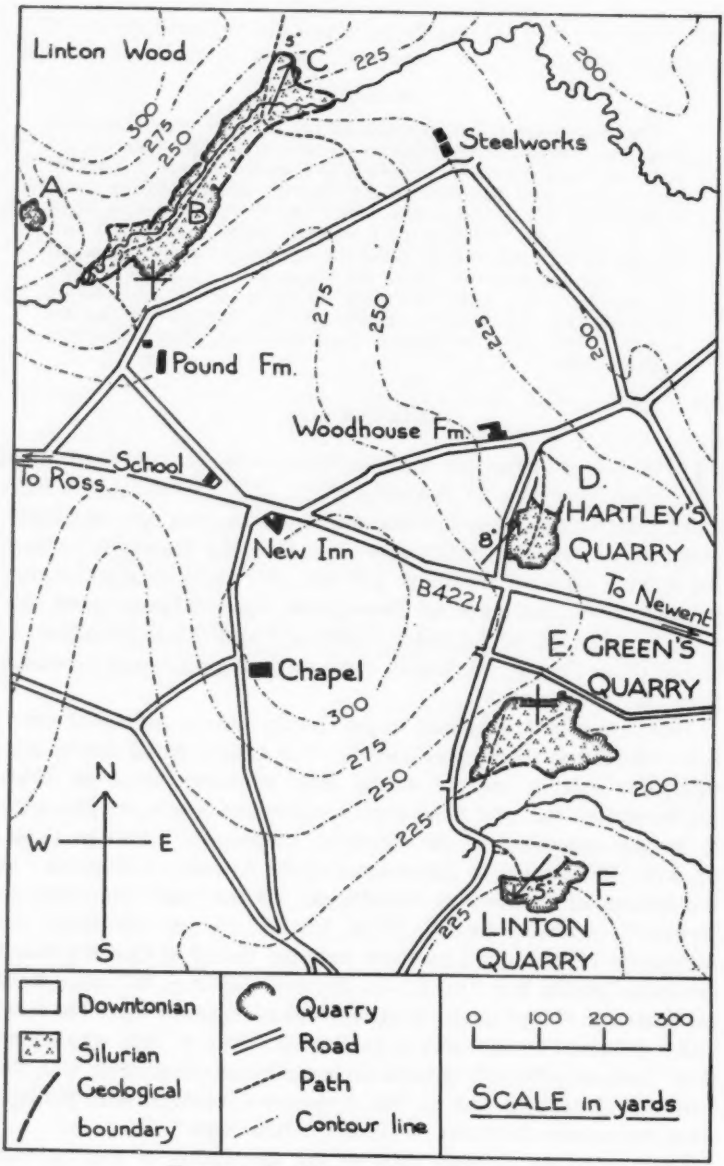
The oldest formation exposed in the Gorsley area is a hard limestone considered by previous authors to be equivalent to the Aymestry Limestone. All the available evidence, however, supports a correlation with the Wenlock Limestone. The succeeding strata comprise 4½ feet of Dayia Beds and 7 feet of Upper Ludlow Beds, so that the total thickness of Ludlovian strata is only 11½ feet. All the Lower Ludlow Shales and the Aymestry Limestone are cut out by the unconformity below the Dayia Beds. This remarkably thin development is attributed to movement at various times during the Ludlovian epoch along an axis passing through the Gorsley region. The main movements probably took place in middle Ludlow times.

Introduction

THE village of Gorsley (Herefordshire) is situated along the main road from Ross to Newent (B 4221), about 5 miles east of Ross and 3 miles west of Newent (Ordnance Survey one-inch map, sheet 143). Geologically, the surrounding area lies in the pitch depression between the Silurian inliers of Woolhope and May Hill and is underlain mainly by sandstones and marls of Downtonian age. Silurian strata are, however, exposed in the valley north of Pound Farm (localities A, B and C on Text-fig. 1), and in three quarries on Gorsley Common (localities D, E, and F).

There are several references to the Gorsley area in geological literature. Murchison (1839, p. 442) wrote: " In Linton Wood, ferruginous sandstone overlies beds of earthy grey limestone, some of which are burnt for lime, and from their position and fossils are presumed to be the equivalent of the Aymestry Limestone." Phillips (1848, pp. 178, 179) referred to the presence of the Aymestry Limestone " at the bottom of a quarry at Woodhouse, on the road from Ross to Newent " (probably locality D in Text-fig. 1), yet mentioned the occurrence of Wenlock Limestone near the Pound in Queen's Wood (probably locality B in Text-fig. 1). Symonds (1872, p. 207) considered the limestone of the Gorsley quarries to be of Aymestry age. The most recent reference to this area is by Pocock (1950, p. 205) who stated that " beds of yellowish carbonaceous sandstone comparable with the Downton Sandstone rest on the Aymestry Limestone with perhaps some intervening thickness of Upper Ludlow Beds ".

The names and symbols used in the description of rock-colours in this paper are based on the Rock-Color Chart published by the Geological Society of America (1951).



TEXT-FIG. 1.—Map of the Gorsley Area.

The Silurian Succession

Linton Quarry (locality F in Text-fig. 1, map reference SO/677 257 has been worked in recent years and provides the clearest and most accessible section through the Silurian rocks. The beds in this quarry dip at about 5° in a direction 50° S. of W. The descending succession is as follows (Text-fig. 2):—

(*f*)	Clifford's Mesne Sandstone	Up to 20 feet exposed
(*e*)	Upper Phosphatized Pebble-bed	$\frac{1}{16}$–$\frac{1}{4}$ inch
(*d*)	Upper Siltstones	7 feet
(*c*)	Lower Phosphatized Pebble-bed	$\frac{1}{16}$–$\frac{1}{2}$ inch
(*b*)	Lower Siltstones	4½ feet
(*a*)	Gorsley Limestone	Up to 12 feet exposed
		Total thickness about 45 feet

(*a*) *Gorsley Limestone.*

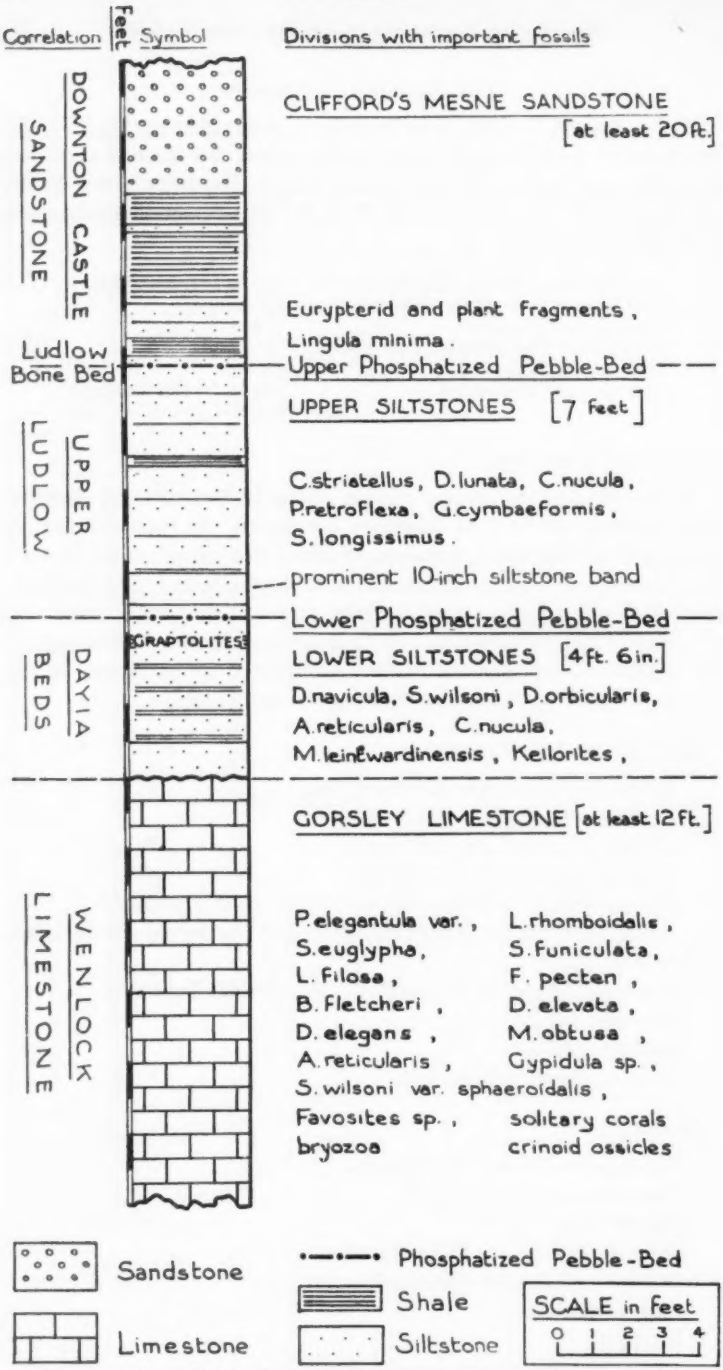
At the base of the quarry section about 12 feet of hard, massive, light bluish-grey (5B 6/1) limestone is exposed. In Hartley's Quarry (locality D in Text-fig. 1), however, 18 feet of this limestone can be seen. The presence of irregular seams and pockets of silt, and the abundance of shell debris suggest strong current action during deposition. On the other hand, the unbroken fossil remains are distributed throughout the limestone, and not normally concentrated in particular bands. The fauna consists mainly of brachiopods and corals.

Common or Fairly Common.

Parmorthis elegantula (Dalman) var.
Leptaena rhomboidalis (Wilckens).
Strophonella euglypha (Hisinger).
Strophonella funiculata (McCoy).
Atrypa reticularis (Linnaeus) var. *lapworthi* Alexander.
Sphaerirhynchia [*Wilsonia*] *wilsoni* (J. de C. Sowerby) var. *sphaeroidalis* McCoy.
Meristina obtusa (J. Sowerby) [= *M. tumida* (Dalman)].
Favosites sp.
Solitary corals.
Crinoid ossicles (abundant).

Present.

Brachyprion fletcheri (Davidson).
Fardenia pecten (Linnaeus).
Gypidula sp.
Delthyris cf. *elegans* Muir-Wood.
Delthyris cf. *elevata* (Dalman).
Camarotoechia sp.
Bryozoa.



TEXT-FIG. 2.—The Geological Succession in Linton Quarry, Gorsley.
(Full generic names of the fossils are given in the fossil lists in the text.)

The Geological Survey Museum collection contains several fossils from the " Aymestry Limestone of Newent, Gloucestershire ". Both the locality description and the matrix suggest that these specimens were collected from the Gorsley Limestone. There are two large specimens of *Meristina tumida* (Dalman) (Nos. 130 and 12268) and two specimens of the gastropod *Platyceras* (Nos. 153 and 36837) labelled " *P. haliotis* Sow. (?*P. cornutum* His.)."

(*b*) *Lower Siltstones.*

These beds rest on the irregular top surface of the Gorsley Limestone and consist of 4½ feet of bluish-grey (5B 6/1), flaggy and shaly calcareous siltstones. The basal bed is a 10-inch band of siltstone. About 4 feet from the base a band of shaly siltstone has yielded *Monograptus leintwardinensis* and *Keilorites squamosa*. Many of the brachiopod shells have been partially or completely replaced by crystalline dolomite, and radiating aggregates of acicular pyrites are not uncommon in some of the cavities. The fauna is as follows:—

Common or Fairly Common.

Dalmanella orbicularis (J. de C. Sowerby).
Chonetes striatellus (Dalman).
Dayia navicula (J. de C. Sowerby) (and from Hartley's Quarry).
Sphaerirhynchia wilsoni (J. de C. Sowerby).

Present.

Dalmanella cf. *lunata* (J. de C. Sowerby).
Atrypa reticularis (Linnaeus).
Camarotoechia nucula (J. de C. Sowerby).
Bucaniopsis sp.
Anodontopsis securiformis McCoy.
Fuchsella [*Orthonota*] *amygdalina* (J. de C. Sowerby).
Paracyclas sp.
Pteronitella retroflexa (Wahlenberg).
Keilorites squamosa (Phillips).
Monograptus leintwardinensis Lapworth.
Scolecodont (from Hartley's Quarry).

(*c*) *Lower Phosphatized Pebble-bed.*

The Lower and Upper Siltstones are separated by an extremely thin ($\frac{1}{16}$–$\frac{1}{2}$ inch) band of phosphatized pebbles of siltstone and mudstone. *Sphaerirhynchia wilsoni* is very common immediately below this band, but has never been found above.

(*d*) *Upper Siltstones.*

The Lower Phosphatized Pebble-bed is succeeded by 7 feet of light

olive grey (5Y 6/1), flaggy and shaly calcareous siltstones. They are similar in lithology to the Lower Siltstones, but current-bedding is more strongly developed. Many of the fossil bands have weathered to an ochreous dark yellowish-orange (10YR 6/6). Faunally, there is a striking contrast with the Lower Siltstone group as *Dayia navicula*, *Sphaerirhynchia wilsoni*, *Dalmanella orbicularis* and *Atrypa reticularis* seem to have disappeared completely, but *Chonetes striatellus* has become abundant.

Common or Fairly Common.

Chonetes striatellus (Dalman).
Camarotoechia nucula (J. de C. Sowerby).
Pteronitella retroflexa (Wahlenberg).

Present.

Orbiculoidea sp.
Dalmanella lunata (J. de C. Sowerby).
Goniophora cymbaeformis (J. de C. Sowerby).
Nuculites sp.
Pterinea sp.
Serpulites longissimus J. de C. Sowerby.

(*e*) *Upper Phosphatized Pebble-bed.*

This thin bed ($\frac{1}{16}$–$\frac{1}{4}$ inch) of phosphatized siltstone and mudstone pebbles separates the Upper Siltstones from the Cliffords Mesne Sandstones. It occurs near the base of a 2-in. band of calcareous siltstone. Fossil remains are very rare and no fish spines or denticles have been found in this bed.

(*f*) *Clifford's Mesne Sandstone.*

The Upper Phosphatized Pebble-bed is followed by 4½ feet of moderate yellowish brown (10YR 6/4) shaly siltstones in which remains of eurypterids and plants are not uncommon. *Lingula minima* J. de C. Sowerby has also been found. Above these shaly beds there succeed about 15 feet of very pale orange (10YR 8/2) sandstone with dark yellowish-orange (10YR 6/6) spots.

Correlation

It is convenient to discuss the correlation of these divisions in descending order so that the most problematical beds (the Gorsley Limestone) may be dealt with last. The comparisons are made with the Shropshire succession as described by Elles and Slater (1906) and Alexander (1936).

(*f*) *Clifford's Mesne Sandstone.*—Both lithologically and faunally

these beds compare closely with the Downton Castle Sandstone formation of other Welsh Borderland areas, although the very pale orange colour of the sandstones is peculiar to the Gorsley district and the northern part of the May Hill inlier.

(*e*) *Upper Phosphatized Pebble-bed.*—The position of this thin bed at the base of the Downton series suggests a correlation with the Ludlow Bone Bed. Fish remains have not been found, but this bed of well-rounded and phosphatized pebbles seems, like the Ludlow Bone Bed, to represent conditions of interrupted deposition.

(*d*) *Upper Siltstones.*—The abundance of *Chonetes striatellus*, the presence of *Dalmanella lunata* and *Serpulites longissimus*, and the absence of *Dayia navicula*, *Dalmanella orbicularis*, *Sphaerirhynchia wilsoni* and *Atrypa reticularis* all support a correlation with a high horizon in the Upper Ludlow Beds of the Shropshire development.

(*c*) *Lower Phosphatized Pebble-bed.*—This thin bed at the base of the Upper Siltstone division is taken to mark an important submarine disconformity involving a long period of interrupted deposition, winnowing and erosion in shallow waters. A similar horizon has been found near the base of the Upper Ludlow Beds in the May Hill district.

(*b*) *Lower Siltstones.*—The characteristically common fossils of this division (*Dayia navicula* and *Sphaerirhynchia wilsoni*) indicate a correlation with part of the Dayia Beds of Shropshire. The discovery of several specimens of *Monograptus leintwardinensis* also supports this correlation. The early abundance of *Chonetes striatellus* is a characteristic feature of the Ludlow developments in the southern and eastern parts of the Welsh Borderland.

(*a*) *Gorsley Limestone.*—The above correlations can be made with some confidence, but the age of the limestone division is more problematical. It can, however, be maintained with reasonable certainty, that the Gorsley Limestone is Silurian in age. Earlier investigators have shown a preference for a correlation with the Aymestry Limestone (see p. 227). It is here contended that the evidence is more in favour of a correlation with the Wenlock Limestone, and that the Ludlow Series is represented by only 11½ feet of strata. The evidence may be considered under three headings: (i) lithological, (ii) palaeontological, and (iii) stratigraphical.

(i) Lithological evidence: The Gorsley Limestone is much harder, purer, and more crinoidal than either the typical Aymestry Limestone or the Woolhope Limestone. It is true that the Aymestry Limestone displays various facies, but its nearest outcrop, three miles to the north at Gwynnes Hill (SO/648 307), is even less hard and less calcareous than the typical Aymestry Limestone of the main Woolhope area.

The Wenlock Limestone in the northern part of the May Hill inlier, 2 miles to the south, is now poorly exposed and much weathered and it is difficult to make a fair comparison with the much fresher Gorsley Limestone. About 8 miles to the N.N.E., however, the large Ledbury quarry (SO/717 384) displays recently worked Wenlock Limestone overlain by Lower Ludlow mudstones. The bedding is perhaps less massive than in the Gorsley quarries but otherwise the two limestones are lithologically identical. This undoubted Wenlock Limestone is very hard and crinoidal; silty seams and pockets are common as in the Gorsley Limestone.

(ii) Palaeontological evidence: The important faunal distinctions between the Aymestry and Wenlock Limestones have been summarized by Alexander (1936, p. 108) but, as she admits, the evidence is often of a negative character. Firstly, there are numerous coral and brachiopod species which are common in the Wenlock Limestone but which have disappeared or become rare in the Aymestry Limestone. Very few of these typical Wenlockian forms occur in the Gorsley Limestone. The abundance of broken shells of *Meristina obtusa* [= *M. tumida* (Dalman)] near the top of the limestone is therefore of importance. Alexander (1936, p. 108) includes *M. obtusa* in a list of Wenlockian brachiopods which are not found in the Aymestry Limestone, and my experience entirely supports her contention. Davidson (1867, p. 111), however, records *Meristella tumida* (Dalman) from " the Aymestry Limestone of Llanbadoc and Russell's Farm ". Assuming the identification of these specimens to be correct, it can still be maintained that the common occurrence of *Meristina obtusa* in a limestone formation is an almost certain indication of a Wenlockian age. Another brachiopod which is common in the Wenlock Limestone, but rare in the Aymestry Limestone, is *Sphaerirhynchia wilsoni* var. *sphaeroidalis*; this form is common in the limestone of the Gorsley quarries. The occurrence of several specimens of *Brachyprion fletcheri*, a species never recorded, to my knowledge, from the Aymestry Limestone, also suggests a Wenlockian age for these beds. Secondly, there are other brachiopods which persist from Wenlock to Ludlow times, but show slight evolutionary changes in the higher limestone. These changes are usually very slight and large numbers of specimens need to be studied statistically if they are to have any positive value. Most of the specimens of *Atrypa reticularis* examined fit into the Wenlock Limestone variety *lapworthi* (see Alexander, 1949, p. 214), but the evidence from the forms of *Strophonella euglypha* and *Strophonella funiculata* is inconclusive. The large unpatterned crinoid ossicles are more characteristic of the Wenlock Limestone than the Aymestry Limestone. Thirdly, there are several fossils which occur in the higher limestone but are not found in the Wenlock Limestone. These include *Dalmanella*

orbicularis, the typical *Chonetes striatellus*, *Lingula lata* J. de C. Sowerby, *Michelinoceras* [*Orthoceras*] *bullatum* (J. de C. Sowerby), *Monograptus tumescens* Wood, *M. leintwardinensis* and *Serpulites longissimus*. None of these species occurs in the Gorsley Limestone and there is thus no positive palaeontological evidence for an Aymestry age. The Dalmanellid brachiopod, on the other hand, compares very closely with *Parmorthis elegantula*, the common Wenlockian species, being much too inequivalve and relatively too long for *Dalmanella orbicularis*. It may be maintained, however, that the presence of a few Wenlockian species should carry less weight than the absence of so many other common Wenlockian fossils (e.g. the compound rugose corals, many solitary corals, and brachiopods such as *Dolerorthis rustica* (J. de C. Sowerby), *Rhynchotreta cuneata* (Dalman), *Camarotoechia lewisii* (Davidson), *Anastrophia deflexa* (J. de C. Sowerby), *Anastrophia rotunda* (J. de C. Sowerby), *Barrandella linguifera* (J. de C. Sowerby) to name only a few). This is a cogent argument, but it may be that many of these species had already departed from the Welsh Borderland area before the end of Wenlockian times. Whether this is the case or not, it is certain that this criticism will apply equally well to the upper Wenlock Limestone of the Ledbury quarry where I have so far failed to find any of the above-named species. The fauna is almost identical with that of the Linton quarry at Gorsley, even to the state of preservation of the Favositid colonies. The following brachiopods have been collected: *Meristina obtusa*, *Sphaerirhynchia wilsoni* var. *sphaeroidalis*, *Strophonella euglypha*, *Delthyris elevata*. Field identifications were made of other fossils, e.g. *Atrypa reticularis* (common), *Leptostrophia filosa* (J. de C. Sowerby), *Parmorthis elegantula* var. (common), *Gypidula* sp., *Favosites* sp. The large unornamented crinoid ossicles appear to be identical with those in the Gorsley Limestone.

(iii) Stratigraphical evidence: In the main Woolhope area the Ludlovian rocks are about 1,000 feet thick, including about 100 feet of Aymestry Limestone. In the southern tongue of the inlier, however, at Whittock's End Farm (SO/659 298), the Aymestry Limestone has disappeared and Dayia Beds rest unconformably on 150 feet of Lower Ludlow Beds. This locality is only 2½ miles N.N.W. of the Gorsley quarries. Less than 2 miles to the S.S.E., in the May Hill inlier, a similar succession occurs (described in a forthcoming paper by the present author). The Aymestry Limestone is cut out by an unconformity at the base of the Dayia Beds, and all the Ludlovian divisions in the May Hill inlier thin towards the Gorsley area. The Upper Ludlow Beds are 60 feet thick near Longhope but only 7 feet at Gorsley, and the Dayia Beds thin from 30 feet at Longhope to 4½ feet at Gorsley. In view of this consistent thinning from both north and south, and the undoubted absence of the Aymestry Limestone at localities so nearby,

it seems most improbable that an isolated and unusually pure development of this limestone should occur in the Gorsley area. Still less probable is it that 1,000 feet of Wenlock Shale and 2–300 feet of Wenlock Limestone could have been overstepped by the unconformable Dayia Beds in such a short distance from the May Hill inlier, so that the possibility of the limestone being the Woolhope Limestone is discounted.

The stratigraphical evidence therefore supports the lithological and faunal evidence in suggesting a correlation of the Gorsley Limestone with the Wenlock Limestone.

Conclusions

The correlation of the Gorsley Limestone with the Wenlock Limestone means that the total thickness of Ludlovian strata in this area is only 11½ feet. The basal phosphatized pebble-bed of the Downton Series rests on 7 feet of Upper Ludlow strata, and indicates a minor unconformity. These Upper Ludlow Beds also develop a phosphatized pebble-bed at their base, and rest directly on 4½ feet of Dayia Beds; the distinctive *Shaleria* [*Brachyprion*] *ornatella* horizon of the Woolhope and May Hill areas (to be described in a forthcoming paper) is cut out by another unconformity. The third, and most important break, is between the Dayia Beds and the Wenlock Limestone, all the Lower Ludlow Beds and the Aymestry Limestone being absent.

No angular discordance has been detected in any of the Gorsley sections, and it is not possible to decide how much of the break is due to non-deposition and how much to erosion following emergence. It seems certain, however, that the Gorsley area lay close to an important axis of uplift in Ludlovian times. The main movements probably took place in the middle of the period as Dayia Beds rest unconformably on Lower Ludlow Shales in the May Hill area, in the southern Woolhope area, and near Leintwardine (Herefordshire) (Alexander, 1936, pp. 111–12). The Sedgley Limestone bone-bed described by Ball (1951, p. 228) from the Gornal (Staffordshire) area may also represent a break at the same horizon.

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On the Graphical Representation of Differentiation Trends in Igneous Rocks

By E. S. W. Simpson

Abstract

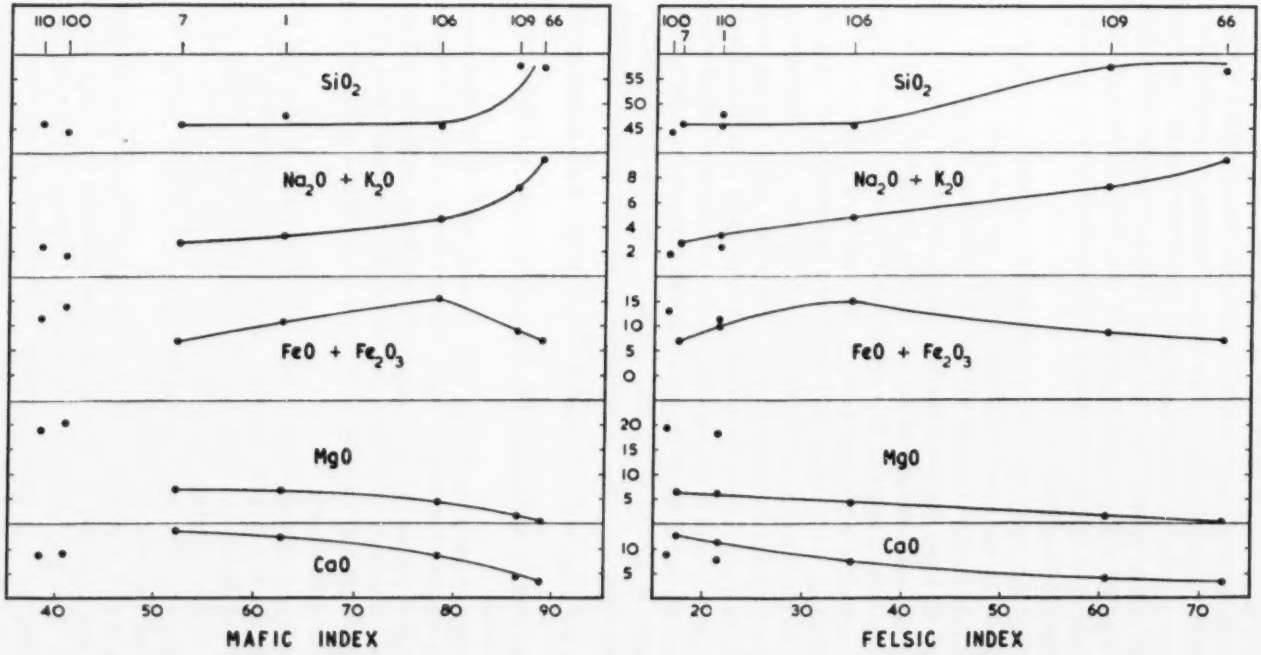
This paper describes a revised method of plotting analyses of igneous rock suites using the Mafic and Felsic Indices as defined. A composite M–F diagram has certain advantages over the triangular iron-magnesia-alkalis diagram and enables a genetic distinction to be made between the tholeiitic and calc-alkaline series.

FOLLOWING upon the earlier work of N. L. Bowen and C. N. Fenner in this field, three recent papers by Poldervaart (1949), Walker and Poldervaart (1949, pp. 650–4), and Tilley (1950, p. 47) have emphasized that differentiation of basic magma broadly involves the fractional crystallization of two contrasted mineral groups, the *mafic* (olivine and pyroxenes together with amphiboles and biotites), and the *felsic* (chiefly feldspars). Together these two groups of minerals make up the bulk of normal " subalkaline " igneous rocks, all other constituents being present usually in accessory amounts. As a supplement to Poldervaart's useful paper an attempt is made here to provide additional criteria whereby the relative influence of the two mineral groups upon the differentiation trend of basic magma may be assessed.

The felsic minerals constitute Bowen's continuous reaction series (1928, pp. 54–62) which experimental work has shown to be enriched in alkalis at the expense of lime during fractional crystallization. The ratio $\frac{(Na_2O + K_2O) \times 100}{CaO + Na_2O + K_2O}$ accordingly provides a convenient index of the degree of fractionation of the felsic minerals and the term *Felsic Index* (F) is proposed. That a certain amount of lime is present in clinopyroxene as well as plagioclase might appear to detract from the usefulness of the felsic index, but comparatively little variation in lime content accompanies the course of pyroxene crystallization even during strong fractionation (Muir, 1951).

The mafic group likewise corresponds to Bowen's discontinuous reaction series, yet each individual mineral series (olivines and pyroxenes in particular) within this group constitutes a continuous reaction series in which fractional crystallization leads to iron enrichment at the expense of magnesia. The ratio $\frac{(FeO + Fe_2O_3) \times 100}{MgO + FeO + Fe_2O_3}$ which was devised by Wager and Deer (1939) may therefore be used as an index of mafic fractionation and is designated the *Mafic Index* (M).

The two indices have been used with some success in analysing the differentiation trend of the Tholeiitic Series of the Okonjeje complex



TEXT-FIG. 1.—Mafic and Felsic linear variation diagrams for the principal oxides of the Okonjeje Tholeiitic Series (110, 100, gabbro-picrites; 7, 1, olivine gabbro; 106, middle ferrogabbro; 109, acid ferrogabbro; 66, quartz syenite).

in South-West Africa (awaiting publication). These rocks show continuous mineral and chemical variation from olivine gabbro through ferrogabbros (which are abnormally enriched in alkali feldspar and show a break in the crystallization of olivine between Fa_{53} and Fa_{60}) to quartz syenite. All available evidence suggests that these rocks, together with associated gabbro-picrites of presumed accumulative origin, have been derived from a parent basic magma by processes of fractional crystallization.

The analysed rocks have been represented graphically by plotting percentages of the more significant oxides against both the Mafic and the Felsic index (Text-fig. 1). The two variation diagrams may be regarded as being complementary. Taking the stage of maximum iron enrichment (represented by the middle ferrogabbro 106) as a convenient reference point, it is evident that the mafic diagram gives a wide spread of points representing the early and middle stages of crystallization, while more acid rocks are represented by crowded points. In extreme cases it is to be expected that the later differentiates might even appear in inverted order. The Felsic index, on the other hand, is the more suitable for tracing the later stages of crystallization, but the general form of the smooth variation curves (which presumably represent the liquid line of descent) is in this example the same whichever index is plotted along the abscissa. The two complementary variation diagrams could be combined by plotting oxide percentages against the mean of the two ratios $\frac{M+F}{2}$ to give a more even spread of points over the whole series, but this method cannot be as satisfactory as the other.

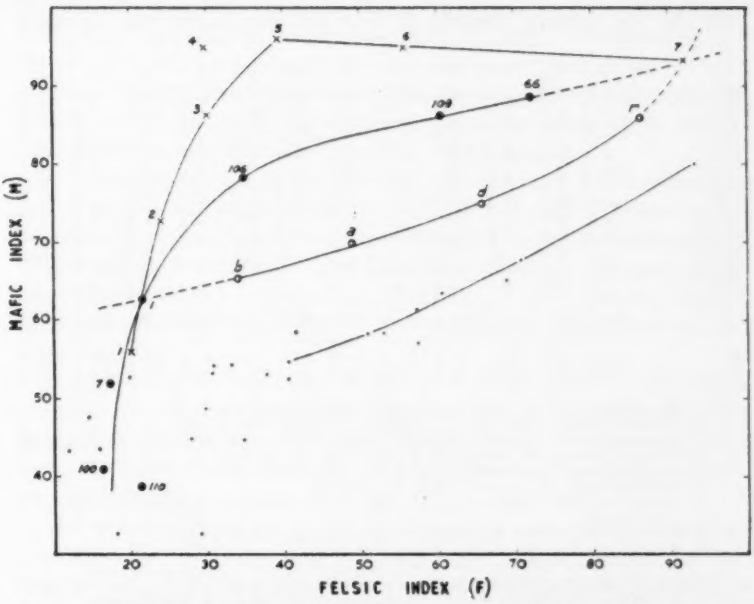
Apart from enabling the variation of each oxide to be traced out over the whole differentiation series, the two linear variation diagrams suggest that during the early and middle stages of crystallization the differentiation trend was influenced mainly by fractionation of mafic minerals, but that the effects of felsic fractionation predominated during the later stages.

A more convincing demonstration of this relation is obtained by plotting the two indices for each analysed rock on a single *M–F* diagram (Text-fig. 2). Data for the Skaergaard liquids (Wager and Deer, 1939), Garabal Hill–Glen Fyne complex (Nockolds, 1941) and Daly's average basalt, andesite, dacite, and rhyolite (Daly, 1933) have been included for comparison.

In each case (with the exception of Skaergaard liquid 4) the plotted points can be joined by smooth curves representing the liquid line of descent. This type of diagram has an added advantage in that the most important factor is the composition of individual phases present in each rock rather than their relative proportions. Thus points repre-

senting rocks of accumulative origin (e.g. 100 and 110 in the Okonjeje complex) lie on the continuation of the curve representing the liquid line of descent, with none of the scattering evident in the linear variation diagrams. Exceptions to this rule are mentioned below.

Like the triangular FMA (total iron-magnesia-alkalis) diagram this type is most useful for demonstrating the contrasted variation trends of the normal calc-alkaline series (as exemplified by the Garabal Hill–Glen Fyne complex and Daly's average basalt, andesite, dacite,



TEXT-FIG. 2.—M–F diagram for Skaergaard liquids (crosses); Okonjeje Tholeiitic Series (black circles); Daly's average basalt, andesite, dacite, and rhyolite (open circles); and Garabal Hill–Glen Fyne complex (dots).

and rhyolite) and the tholeiitic series which commonly show iron enrichment (cf. Poldervaart, 1949, pp. 180–3; Walker and Poldervaart, 1949, pp. 656–662; Tilley, 1950, pp. 47–9; Nockolds and Allen, 1953). In the Skaergaard intrusion alkali enrichment (i.e. felsic fractionation) is strongly suppressed during the early and middle stages of crystallization, but becomes suddenly predominant during the later stages while the residual five per cent of the magma is crystallizing (Wager and Deer, 1939, pp. 234–5). As shown by the differentiation trend in Text-fig. 2, iron enrichment becomes "negative" during this stage. In the Okonjeje rocks both mafic and felsic fractionation

have operated simultaneously to influence the trend of differentiation, the former being dominant up to the stage of maximum iron enrichment and felsic fractionation during the later stages. The effect of early and steadily increasing felsic fractionation is clearly reflected in the lower degree of iron enrichment and pronounced zoning of plagioclase crystals in this series as compared with the Skaergaard rocks.

A rock series developed by strong non-selective fractionation of both mafic and felsic constituents should be represented by a straight line at an angle of 45 degrees to the abscissa. Such a theoretical straight line forms a tangent to both the Skaergaard and Okonjeje

	A	B	C	D	E	F	G	H	I	J	K	L
SiO_2	47·8	47·9	52·5	48·4	48·2	49·1	50·8	75·0	72·8	73·7	70·2	72·1
TiO_2	1·5	1·4	1·0	1·3	1·0	1·4	2·0	0·3	0·3	0·2	0·4	0·4
Al_2O_3	16·8	18·9	15·4	16·8	17·9	15·7	14·1	13·2	13·3	13·4	14·4	13·8
Fe_2O_3	2·7	1·2	1·2	2·5	3·2	5·4	2·9	1·6	1·4	1·3	1·6	0·9
FeO	8·5	8·6	9·3	7·9	6·0	6·4	9·1	0·6	1·0	0·8	1·8	1·7
MnO	0·2	0·1	0·2	0·2	0·1	0·3	0·2	—	0·1	—	0·1	0·1
MgO	6·7	7·8	7·1	8·1	7·5	6·2	6·4	0·1	0·4	0·3	0·9	0·5
CaO	12·0	10·5	10·3	11·1	11·0	8·9	10·4	0·7	1·2	1·1	2·0	1·3
Na_2O	2·5	2·4	2·1	2·3	2·5	3·1	2·2	4·2	3·3	3·0	3·5	3·1
K_2O	0·8	0·2	0·8	0·6	0·9	1·5	0·8	3·8	4·6	5·3	4·1	5·4
H_2O+	0·1	0·4	—	0·6	1·4	1·6	0·9	0·3	1·5	0·8	0·8	0·5
H_2O-	0·4	0·1	—	—			—	0·1		—		—
P_2O_5	0·3	0·1	0·1	0·2	0·3	0·4	0·2	—	0·1	0·1	0·2	0·2
	100·3	99·6	100·0	100·0	100·0	100·0	100·0	99·9	100·0	100·0	100·0	100·0
M	62·7	55·8	59·7	56·4	55·0	65·4	65·6	93·5	86·3	86·2	79·1	83·8
F	21·6	20·0	21·0	19·8	22·2	34·2	21·8	92·1	86·7	88·2	79·1	86·9

A Outer Ridge Gabbro, Okonjeje complex, South-West Africa.
B Average Skaergaard chilled phase (Wager and Deer, 1939, p. 141).
C Average Karroo dolerite, forty-three analyses (Walker and Poldervaart, 1949, p. 649).
D Average gabbro, 160 analyses (S. R. Nockolds, unpublished).
E Average gabbro, forty-one analyses (Daly, 1933, p. 17).
F Average basalt, 198 analyses (Daly, 1933, p. 17).
G Average tholeiitic basalt and quartz dolerite, 137 analyses (S. R. Nockolds, unpublished).
H Acid granophyre 3058, Skaergaard (Wager and Deer, 1939, p. 208).
I Average rhyolite, 102 analyses (Daly, 1933, p. 9).
J Average normal rhyolite, twenty-two analyses (S. R. Nockolds, unpublished).
K Average granite of all periods, 546 analyses (Daly, 1933, p. 9).
L Average normal granite, seventy-two analyses (S. R. Nockolds, unpublished).

trends at points approximating to the stage of maximum iron enrichment in each case. The point of contact thus represents the stage at which the effects of mafic and felsic fractionation are balanced.

The effects of strong selective mafic fractionation are represented by the Skaergaard rocks, while the trend shown by Daly's average basalt, andesite, dacite, and rhyolite is characteristic of that to be expected for rocks derived by selective felsic fractionation. Precisely why selective fractionation should take place is indeed a problem, no doubt involving such characteristics of the parent magma as degree of oxidation of iron, relative abundance of volatiles, and proportion of alkalis.

The Garabal Hill–Glen Fyne series, though poorer in iron, follows a trend parallel to that of Daly's average rocks. The marked scattering

of points representing rocks more basic than the parent pyroxene-mica-diorite (Nockolds, 1941, pp. 496–7) as opposed to the linear trend of the more acid rocks must be due to the lime content of mafic accumulative rocks. This point illustrates a disadvantage of the *M–F* diagram in that accumulative rocks of pyroxenitic and amphibolitic composition will give rise to scattered points.

In spite of these greatly differing trends during the intermediate stages of crystallization, it is notable that the curves (or their continuations) for the Skaergaard, Okonjeje, and Daly's average rocks commence from a common starting point roughly corresponding to the Okonjeje olivine gabbro 1, and later converge towards a common residual differentiate represented by the Skaergaard acid granophyre 3058 (liquid 7). The analyses of these two rocks are set down on p. 242 together with some world averages for comparison.

A further disadvantage, shared with the triangular FMA diagram, is that the plotted points and curves fail to give a proportionate representation of the time and volume relations of successive differentiates. Wager and Deer (1939) have overcome this difficulty by plotting oxide percentages against "percentage solidified", but igneous bodies for which progressive variation of this value can be calculated must be extremely rare.

Finally it should be noted that the *M–F* diagram does not provide a means for distinguishing between the alkaline trend on the one hand and the calc-alkaline and tholeiitic trends on the other (cf. Peacock, 1931), except that alkaline rock series do not normally show iron enrichment.

The author wishes to record his thanks to Dr. Morna Mathias and Professor A. Poldervaart for their constructive criticism of the ideas presented in this paper, and to Dr. S. R. Nockolds for permitting use to be made of unpublished averages of rock analyses.

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A Note on the Occurrence of Columbite in the Younger Granites of the Jos Plateau, Nigeria

By T. U. JOHN and K. L. PAULO

(PLATE V)

ABSTRACT

Of the various members of the Younger Granite Complex columbite is found only in the biotite granites. It occurs as an accessory mineral, and varies in amount in different types.

I. INTRODUCTION

UNTIL a few years ago very little was known about the primary occurrence of columbite on the Plateau of Nigeria, due mainly to the fact that it was then less important economically than it is now, and was regarded only as a by-product of the cassiterite won by alluvial mining methods. The Geological Survey officers had made observations on its mineralogical properties but had recorded only briefly its occurrence as a primary accessory mineral in the Younger Granites.

In July, 1950, Amalgamated Tin Mines of Nigeria, Ltd., detailed the writers to begin an investigation of the problem, which had been touched upon by one of us during the previous year. The work was mainly of local interest ; but in view of the present great demand for columbite and the scientific interest of its occurrence, we record some of the main results in this note.

REVIEW OF LITERATURE

In 1946 Dr. Jacobson of the Nigerian Geological Survey (Jacobson, 1946), mentioned the presence of columbite in decomposed biotite granite at Bassa, west of Jos, which was first discovered by Colonel Dent-Young. He also records the mineral from the Liruein Kano Hills. Columbite is recorded by the Geological Survey department in the pegmatites of Central Nigeria (Jacobson and Webb, 1946). These seem to be the only references to the primary occurrence of columbite up to the time of our investigation, but a useful summary has recently been issued by the Geological Survey of Nigeria, recording other localities investigated by their Department and by the geologists of Amalgamated Tin Mines of Nigeria, Ltd. (Jacobson, Cawley, and Macleod, 1951). This contains much useful information. The mineralogical properties of Nigerian columbite have been recorded by Dr. Tattam and by Dr. J. S. Webb, in unpublished reports of the Geological Survey of Nigeria.

II. Geological Setting

The Jos Plateau of Nigeria consists mainly of the Nigerian Granite Complex, intruded into the Basement of gneisses and Older Granites. It is the greater resistance to erosion of the Younger Granites which makes the Plateau stand well above its surroundings. The intrusions include quartz-porphyries, granite-porphyries, and riebeckite granite, but they are mainly of biotite granite. Rhyolite also occurs, probably as flows. There are Tertiary basalts and also some basalts of recent age, which have in some cases preserved beneath them alluvial deposits of cassiterite and, in places, some of alluvial columbite. The geology is described by the Nigerian Geological Survey (Mackay, Greenwood, and Rockingham, 1949).

III. Work Done

In the middle of 1950 many granitic rock types on the Plateau were studied for the presence of columbite. Briefly, the method was to crush the rock and separate the heavy minerals by careful panning. Columbite was found to be one of the primary accessory heavy minerals in the biotite granite phases of the complex Younger Granite intrusions.

In 1949 one of the writers had confirmed the presence of columbite in the normal biotite granite at Bassa, west of Jos. To exclude other possibilities we examined all the other members of the Younger Granite complex, and also the Older Granites. All were barren, and sufficient proof was obtained that it is only the biotite granite which contains columbite. A somewhat patchy dissemination of columbite was observed at this stage, and the mode of occurrence pointed to the fact that it is an accessory mineral of the biotite granites.

The Geological Survey of Nigeria carried the investigation further and by 1952 W. N. Macleod had mapped the Jos-Bukuru Younger Granite mass in detail; he has shown (in a report not yet published) that certain phases of biotite granite are richer in columbite than others.

IV. Primary Occurrence of Columbite

It was found that crystals of columbite occur in all types of biotite granite. The best results were obtained from the medium and evenly grained variety, while very little or no columbite was found in the coarse-grained type. The former variety is a beautiful sugary granite with greyish quartz evenly sprinkled in the white background of feldspar. The size of the columbite crystals in this rock varies a good deal. Some crystals are plus 40 IMM mesh, but a far bigger proportion passes through 100 IMM mesh. It is known that the size of columbite is very small indeed, and recently F. A. Williams of Amalgamated

Tin Mines of Nigeria, Ltd., found that in one case 30 per cent of the columbite was minus 200 IMM mesh. Occasionally, however, larger crystals occur, of both acicular and platy varieties.

Microgranitic varieties usually contain markedly less columbite than the medium-grained type, but the coarse type contains even less. This observation was later confirmed by W. N. Macleod.

A feature of the columbite of the Plateau is its prismatic development, which is sometimes extreme, when the crystals become quite acicular. This acicular habit does not seem to have been described from any other locality. The longest crystal we have measured is 4·3 millimetres long, but it had been broken off at both ends. It is an extremely slim crystal, with ratio of length to width of about 20 to 1.

Columbite is found in tiny acicular or platy crystals, singly or in small randomly oriented clusters enclosed in quartz or feldspar, and columbite has been seen to occur in quartz and biotite. Crystals larger than, say, 1·5 millimetres have not been seen intact and unbroken; actually they have been seen already broken in the rock before its disintegration. Close examination reveals that the crystals break or bend along the contacts of two or more host minerals. In some cases needles are broken and minutely displaced, and quartz or feldspar has entered and healed the fracture. Apparently columbite was the first mineral to crystallize out of the magma, and due to their brittleness the crystals broke in the last stages of the consolidation of the rock when intercrystalline adjustments took place.

Conclusive evidence of the occurrence of columbite as an accessory mineral of the biotite granite was obtained when we prepared thin sections of this granite from the Rukuba Hills, west of Jos (see Plate V). The slides could not be cut very thin for fear of destroying the crystal contours, and it is extremely difficult to obtain a section with columbite lying exactly in the plane of the section. This was the first time columbite had been identified in a thin section in the Nigerian granites. The microphotographs were prepared by the Geological Survey Department of Nigeria.

V. Acknowledgments

Acknowledgment is due to the management of Amalgamated Tin Mines of Nigeria, Ltd., for permission to publish this paper; to L. H. Cruden for help in the laboratory; to F. A. Williams, Chief Geologist; and to J. L. Farrington, at that time Consulting Geologist, who introduced us to the subject. Thanks are also due to the Director of the Geological Survey of Nigeria, in whose department the microphotographs were prepared.

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EXPLANATION OF PLATE V

All figures are of biotite granite from the Rukuba Hills, west of Jos, Nigeria.

FIG. 1.—Acicular crystal of columbite in quartz. This is a typical form of columbite in the Younger Granite. Ordinary light. × 35.

FIG. 2.—A relatively stubby crystal of columbite included in a large crystal of quartz. Ordinary light. × 35.

FIG. 3.—Two columbite crystals at the boundary between quartz and feldspar. They formed part of a cluster, most of which has been ground away. Ordinary light. × 35.

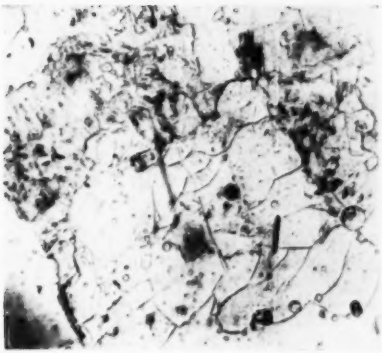

FIG. 1

FIG. 2

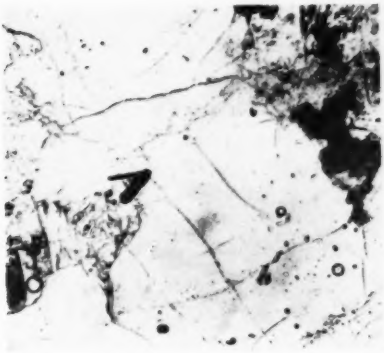

FIG. 3.

COLUMBITE CRYSTALS IN BIOTITE GRANITE, RUKUBA HILLS, NIGERIA.

A New Ampthill Clay Fauna from Knapwell, Cambridgeshire

By J. M. Hancock

Abstract

A new ammonite assemblage from the Ampthill Clay is recorded. Its correlation with the *Trigonia clavellata* beds of Dorset indicates that these condensed beds are represented by two distinct horizons in the Ampthill Clay—the Boxworth Rock below and the Knapwell Ditch horizon above.

During the winter 1952–3 a stream running northwards from Knapwell, a hamlet 8 miles W.N.W. of Cambridge, was deepened, exposing and partly excavating a section in the Ampthill Clay. My friend, Mr. B. Butler, collected some specimens from the tip-heaps and section which on examination were found to include *Perisphinctes* (*Pseudarisphinctes*) spp. and *Decipia* spp. Further collecting with Dr. Arkell and other friends, provided material that indicates that this is probably a level not seen before in the Ampthill Clay.

The deepened part of the stream runs from a point 400 yards north of Knapwell Church (Grid Reference 336634) to a point 1,400 yards N.N.E. of the church (G.R. 330641), where it runs underneath the Elsworth–Boxworth Road. Near the road a limestone band in the clay shows a low dip to the south; there is no obvious indication of any change of dip along the length of the exposure. All the ammonites except one were obtained within 500 yards of the road. Some were extracted from the limestone band itself but most were collected from the tip-heaps beside the stream. The forms represented are:—

Decipia decipiens (J. Sowerby)

Decipia lintonensis Arkell

Perisphinctes (*Pseudarisphinctes*) *pachachii* Arkell

P. (*Pseudarisphinctes*) ? *durnovariae* Arkell

A perisphinctid with a trumpet-shaped aperture.

Gryphaea dilatata J. Sowerby, commonly large and encrusted with the usual serpulids.

Of the ammonites in this main assemblage, only *D. decipiens* has been found before in the Ampthill Clay, sometimes with "*Ammonites plicatilis*" (see Roberts, 1889). Blake (1875) recorded it with various species, particularly at Market Rasen in Lincolnshire. Amongst these is "*Ammonites*" *berryeri* Lesueur, which is a name that Blake and Hudleston (1877) used for a specimen of *Decipia lintonensis* from the Upper Calcareous Grit of Kirkdale cutting in Yorkshire (see Arkell, 1935–1948, p. 47). This occurred at Kirkdale with *Decipia decipiens* and the only other occurrence of *D. decipiens* outside the Ampthill Clay, at Steeple Ashton in Wilts, was probably from the *Trigonia clavellata* beds, the horizon of *D. lintonensis* in Dorset (three

specimens known). The holotype of *D. lintonensis* came from the upper part of these beds. The only specimen of *D. lintonensis* known previously from the Ampthill Clay is a magnificent specimen, 254 mm. in diameter, from " 300 yards south of chalybeate spring, Bathe Hill, 2 miles N.N.E. of St. Ives, Hunts ", in the Geological Survey collection (SEH 307).

P. durnovariae is known from the *Trigonia clavellata* beds of Dorset (one specimen), and the equivalent Couches d'Hennequeville of Normandy (one specimen) (see Arkell, 1935–1948). *P. pachachii* was previously known only from one specimen from the Red Beds (upper part of the *Trigonia clavellata* beds) of Dorset.

The assemblage thus correlates with the upper part of the Dorset Trigonia beds. The Boxworth Rock below the Decipiens zone has already been correlated with the same horizon (see Arkell, 1935–1948, p. 52), but contains no species in common with the present assemblage. The Dorset Red Beds were inferred to be condensed, on their facies and variety of species, by Arkell, in 1935 (p. 9). This is supported now by the fact that they are represented by at least two distinct horizons in the Ampthill Clay—the Boxworth Rock below and the Knapwell Ditch limestone in the clay above.

Most of the material in the assemblage is preserved as body-chambers only. I have therefore compared them with the body-chambers of *Decipia* (*Pomerania*) spp. from Long Stanton (see Arkell, 1937, and 1935–1948), to which most of the specimens bear at least a superficial resemblance. The *Pseudarisphinctes* spp. are readily distinguished by their thicker whorl-section and their coarser, sometimes bulbous ribbing. As might be expected, the *Decipia* spp. are harder to distinguish. *D. lintonensis* is very close in ribbing and whorl-section to *D.* (*Pomerania*) *dewari* Arkell, but in the later stages of *D. dewari* the ribbing again crosses the venter, whereas in *D. lintonensis* it fails to do so. In general *D. lintonensis* is a smaller species. One example in the present collection is mature at a diameter of approximately 265 mm. On the other hand the specimen of *D. lintonensis* from Pickering, Yorkshire (figured, Arkell, 1935–1948, pl. lxxviii, fig. 6) has a diameter of 316 mm. The other *Pomerania* spp. show markedly different whorl-sections at equivalent diameters, apart from differences in the ribbing.

The perisphinctid with the trumpet-shaped aperture is almost unique. From the drift at Cranford, Northants, there is an incomplete body-chamber of a *Decipia* sp. with a trumpet-shaped aperture.

Near the south end of the section a single specimen of *Perisphinctes* (*Ampthillia*) *ampthillensis* Arkell was found on the tip-heap, which probably came from another limestone band to be seen in the stream near by. This species was found at Long Stanton reservoir, and the southern end of the Knapwell section may well be approaching that horizon. There is no suggestion that the northern end of the Knapwell

ditch is at the same level as Long Stanton reservoir, the general composition of the fauna being quite different; in particular, no *Amoeboceras* was found in the large amount of material excavated from the Knapwell ditch, whereas *Amoeboceras* of several species were the most abundant fossils at Long Stanton reservoir.

The ammonite horizons now known in the Ampthill Clay are:—

(*d*) *Perisphinctes* (*Perisphinctes*) *variocostatus* and *Amoeboceras prionodes* beds (known from Drift mainly but exposed in drains at Manea, Cambridge, and Woodhall Spa, Lincs).

(*c*) *Amoeboceras pseudocaelatum* beds with *Decipia decipiens* (known from drains at Mepal, near Cambridge, at Fordy's Farm, between Ely, Streatham, and Soham, and in a boring at Severals House, Norfolk). The Long Stanton reservoir is probably on a close but not quite identical horizon, judging by the many *Pomerania* spp. and different preservation of the ammonites. *D. decipiens* was not found in the Severals House boring, but at the other localities the *Amoeboceras* occurred a few feet above the *Decipia*-bearing limestone.

(*b*) *Decipia lintonensis*, *D. decipiens*, *Pseudarisphinctes* spp. assemblage (Knapwell Ditch).

(*a*) Boxworth Rock with *Perisphinctes osmingtonensis* and *Amoeboceras glosensis*.

Below this comes the Plicatilis zone to which belong all the ammonites known from the Upware Corallian and from the Elsworth and St. Ives Rocks.

Still earlier is the Elsworth Rock facies below the Upware Corallian limestones, which is equivalent to the lower Elsworth Series at Elsworth, i.e. Cordatus zone.

I am much indebted to Dr. W. J. Arkell, who made the first identifications of the ammonites and has given me much help and advice in the preparation of this note. Mr. R. V. Melville kindly arranged for me to borrow the Geological Survey material from Long Stanton. The work has been carried out whilst in receipt of a grant from the Department of Scientific and Industrial Research.

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CAMBRIDGE.

A New *Palaeechinus* from Alberta

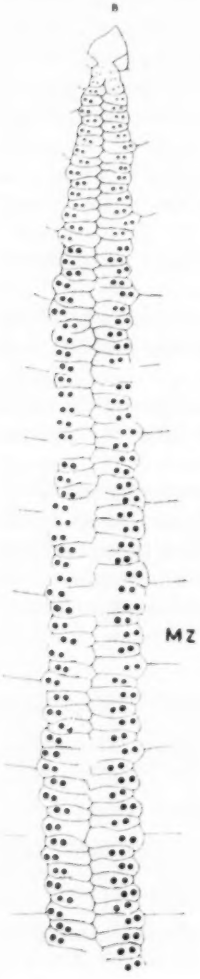
By Porter M. Kier

Abstract

A new species of *Palaeechinus* from the Lower Carboniferous of Alberta is described.

Introduction

DR. A. C. SPRENG has most kindly sent me an echinoid which he collected in the Banff Formation in Alberta. The specimen is fairly well preserved and represents a new species. I want to thank Dr. Spreng for his kindness in sending the specimen to me, and Mr. A. G. Brighton for his criticism and suggestions.



Text-fig. 1.—*Palaeechinus sprengi* sp. nov. View of ambulacrum B in the holotype showing plates uniserial near apical area but almost biserial at midzone. × 2. (Approximate location of midzone indicated by letters *mz*.)

Family Palaeechinidae M'Coy

Genus palaeechinus M'Coy

Palaeechinus M'Coy, 1844, p. 171

Type Species.—By subsequent designation, *Palaeechinus ellipticus* M'Coy, Lambert and Thiéry, 1910, p. 119.

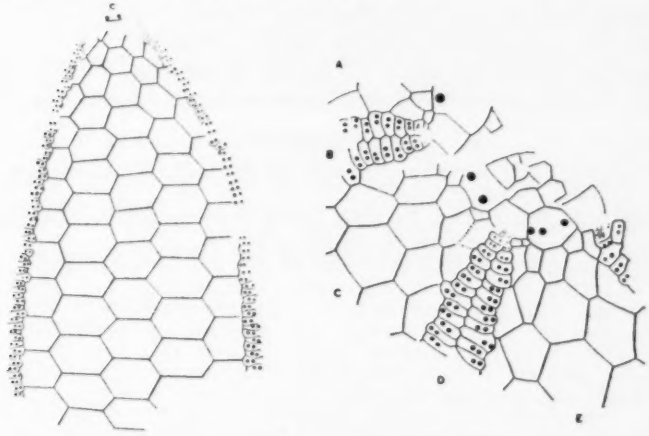
Palaeechinus sprengi sp. nov.

Diagnosis.—This species is characterized by an elliptical test with five columns of wide plates in each interambulacrum. There are usually six ambulacral plates for each adambulacral plate.

Material.—One specimen, the holotype, in which two ambulacra and interambulacra are preserved. Approximately one-half of the apical system is preserved but the peristome and the oral portion of the ambulacra and interambulacra are missing. The specimen is in the collections of the Geological Survey, Department of Mines and Resources, Ottawa.

Description.—Shape: The test is high, elliptical, and was probably originally when complete about 40 mm. high and 33 mm. in diameter. At the midzone, the ambulacrum is about 4 mm. wide, and the interambulacrum 15 mm. wide. The adradial sutures are depressed.

Apical System.—Only about one-half of the apical system is preserved. Two genitals and a portion of a third are visible; there are two genital pores in one, three in the other. The third genital plate was evidently much larger than the others but the character of the plate is not clear. The oculars are imperforate, very large, nearly as large as the genitals. The periproctal plates are irregular.



TEXT-FIG. 2.—*Palaeechinus sprengi* sp. nov. (*a*) View of interambulacrum and adjoining ambulacra of holotype. × 1·5.
(*b*) View of apical system of holotype showing large oculars. × 3.

Ambulacra.—The ambulacra are narrow, with two columns of primary plates in each area and with six plates equal to the height of an adambulacral plate; the pore-pairs are irregularly uniserial. At the midzone, although all the plates are primaries, they are alternately narrowed and broadened at the adradial margins, and the pore-pairs are almost biserial; the outer pore of one plate is almost in line with the inner pore of the succeeding plate. The ambulacra are identical with those of *Palaeechinus canadensis* Kier. (Kier 1953.)

Interambulacra.—Wide with five columns of plates at the midzone. The adambulacral plates are typically pentagonal; the plates of the median columns are hexagonal, wider than high. No terminal plates are preserved.

Ornamentation.—The plates of the test are covered with the numerous secondary tubercles common in the species of the *Palaeechinidae*.

Comparison with other Species.—This species is quite similar to *Palaeechinus ellipticus* M'Coy from the Lower Carboniferous of Ireland. Both species have an elliptical test with five columns of interambulacral plates. This Canadian species is distinguished by its wider interambulacral plates and by having only six ambulacral plates to each adambulacral plate as compared with seven–eight in *P. ellipticus*. Unfortunately the apical system is not visible in *P. ellipticus* and comparison cannot be made of this important feature.

This species differs from *Palaeechinus canadensis* from lower in the Banff Formation by having five instead of eight columns of interambulacral plates, and by having larger oculars.

Horizon.—Lower Carboniferous–Banff Formation.

Locality.—Collected by A. C. Spreng at Sunwapta Pass in Banff Park, very near the Banff–Jasper Park boundary in Alberta, Canada.

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CORRESPONDENCE

THE STROLLAMUS AREA OF SKYE

SIR,—Two recent papers by Sir Edward Bailey published in the *Geological Magazine* present a review of earlier work in this area and offer interesting reinterpretations.

The papers are essentially attempts to reconcile field observations with two assumptions by Bailey:—

(*a*) that since the Torridonian of Scalpay appears to be autochthonous, that on Creag Strollamus is likely to be structurally similar, in contradistinction to the undoubtedly allochthonous character of the Torridonian south of Broadford,

(*b*) that Tertiary basalts, if normal extrusive lavas, necessarily near on Mesozoics, so that their juxtaposition with Torridonian in the Strollamus area is to be explained otherwise than by unconformity.

In the first paper Bailey concludes that whereas Cambrian outcrops near Broadford are " windows " in the overlying Torridonian, closely comparable outcrops on the south-eastern slopes of Creag Strollamus are klippen resting on Torridonian.

The only direct evidence that Bailey offers for his view is to be found at a locality a mile west of Broadford where he " thinks it practically demonstrated that we have in this case a window which in the past has been mistaken for a group of klippen ". This alone of the " local appearances " is, Bailey considers, to be accepted " as trustworthy ", since it enables the Torridonian of Creag Strollamus and Scalpay to be regarded alike as autochthonous.

In fact, however, in the Creag Strollamus area all the observational data consistently support Harker's original view. Where the boundaries are irregular in plan, the Cambrian forms well-marked topographic depressions below the encircling Torridonian, the clearest example being seen to the south-south-west of the summit. At the southern end of this " window ", Cambrian occupies the floor and Torridonian the sides of a gully. On the south side of a small gorge formed by the upper course of Allt Fearna an actual junction is seen between Cambrian and overlying Torridonian.

Faults have not been invoked, as Bailey seems to imply, merely to overcome difficulties in supposing all Torridonian-Cambrian boundaries to be thrust. In many cases the faults can actually be seen and in upper Allt Fearna both the sub-horizontal thrust-plane and a vertical fault may be recognized in the same exposures. Indeed detailed mapping shows that the faults form a distinct NE–SW pattern, often determining stream courses and minor scarp features.

In the second paper Bailey infers that the Strollamus lavas do not rest unconformably on Torridonian but occupy a " volcanic inbreak ". This he claims as the " obvious alternative " explanation for the elaborate junction between basalts and Torridonian on the steep north-eastern slopes of the hill. That at this junction the lavas are often transgressive in detail was clearly recognized (King, 1953, p. 361), but there are also numerous places at which it can be shown that the lavas are no more than a thin veneer resting on Torridonian. Moreover, on the larger scale the supposition that the basalts irregularly and quite fortuitously cut through the Torridonian is difficult to reconcile with their perfectly regular trap-featuring. The " shattering " which is often seen in the Torridonian and which Bailey (p. 111) cites as evidence that the " Torridonian was upheaved alongside the Strollamus sink " affects basalts, gabbros and granites alike, so that its connection with the volcanic episode is questionable. The analogy Bailey (p. 112) implies between the small, highly irregular penetrations of basalt into Torridonian and the well-defined dykes and boss-like masses farther to the south-west does not represent a fair appraisal of the observational data.

Bailey makes no reference to the innumerable little sheets and occasional dykes of " dark and xenolithic porphyries " (King, *op. cit.*, p. 393) which are prevalent around the Torridonian-basalt boundary throughout the area.

These are light weathering rocks of andesitic affinities, often closely resembling the finer-grained Torridonian rocks in the field and could easily confuse observation during a cursory visit to the area. Even on the large-scale map (King, *op. cit.*, Plate I) it has been quite impossible to represent these minor intrusive masses in their entirety. Bailey (p. 110) having apparently collected and sectioned this material, has concluded that the crag at the summit of the steep face of Creag Strollamus consists wholly of andesite, which he seems to regard as belonging to the lava series.

Why Bailey (p. 113) should refer to the Broadford gabbro as " dolerite " is difficult to understand. Much of it is considerably coarser in texture than many Tertiary gabbros. Perhaps the term is used because it gives an air of greater probability to the interpretation of the narrow belt of gabbro as a dyke. It is apparent from the field relations that this belt is not a dyke in the ordinary sense and the indications that it is bounded by faults are very clear (King, *op. cit.*, pp. 373–4). It is, however, to be emphasized that the form of the gabbro belt and its structural relations with the Broadford gabbro, a relationship which Bailey makes no pretence at understanding, are to be judged quite independently of the *hypothesis* that the gabbros represent metamorphosed lavas (King, *op. cit.*, p. 382).

Regarding Bailey's " speculation " (p. 114) as to the mode of emplacement of the gabbro within the Durness limestone, one can only express bewilderment at such a grotesque solution to the space problem. If it is difficult to understand how a given volume of limestone has been replaced by the *same* volume of gabbro, how much more difficult is it to imagine *very many times* this volume of " subterranean acid water " dissolving the limestone " before or during the arrival of magma on the scene ". Apparently the gabbro magma was erupted into limestone caves.

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19th April, 1954.

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